Received 26 October 2023, accepted 13 November 2023, date of publication 16 November 2023,
date of current version 27 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3333441

RESEARCH ARTICLE

Private Blockchain Envisioned Access Control System for Securing Industrial IoT-Based Pervasive Edge Computing

SOURAV SAHA[1], **BASUDEB BERA**[1], **ASHOK KUMAR DAS**[1], **(Senior Member, IEEE), NEERAJ KUMAR**[2], **(Senior Member, IEEE), SK HAFIZUL ISLAM**[3], **(Senior Member, IEEE), AND YOUNGHO PARK**[4], **(Member, IEEE)**
[1]Center for Security, Theory and Algorithmic Research, International Institute of Information Technology, Hyderabad 500032, India
[2]Department of Computer Science and Engineering, Thapar University, Patiala 147004, India
[3]Department of Computer Science and Engineering, Indian Institute of Information Technology Kalyani, Kalyani, West Bengal 741235, India
[4]School of Electronics Engineering, Kyungpook National University, Daegu 41566, Republic of Korea

Corresponding authors: Ashok Kumar Das (iitkgp.akdas@gmail.com) and Youngho Park (parkyh@knu.ac.kr)

This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under Grant 2020R1I1A3058605; in part by the Blockchain Project through the Ripple Centre of Excellence (CoE) Scheme, CoE in Blockchain, International Institute of Information Technology Hyderabad (IIIT Hyderabad), India, under Grant IIIT/R&D Office/Internal Projects/Ripple/2021-22/009; and in part by the Unified Blockchain Framework for offering National Blockchain Service, Ministry of Electronics and Information Technology, New Delhi, Government of India, under Grant 4(4)/2021-ITEA.

ABSTRACT The Industrial Internet of Things (IIoT) is able to connect machines, analytics and people with IoT smart devices, gateway nodes and edge devices to create powerful intuitivenesses to drive smarter, faster and effective business agreements. IIoT having interconnected machines along with devices can monitor, gather, exchange, and analyze information. Since the communication among the entities in IIoT environment takes place insecurely (for instance, wireless communications and Internet), an intruder can easily tamper with the data. Moreover, physical theft of IoT smart devices provides an intruder to mount impersonation and other attacks. To handle such critical issues, in this work, we design a new private blockchain-envisioned access control scheme for Pervasive Edge Computing (PEC) in IIoT environment, called PBACS-PECIIoT. We consider the private blockchain consisting of the transactions and registration credentials of the entities related to IIoT, because the information is strictly confidential and private. The security of PBACS-PECIIoT is significantly improved due to usage of blockchain as immutability, transparency and decentralization along with protection of various potential attacks. A meticulous comparative analysis exhibits that PBACS-PECIIoT achieves greater security and more functionality features, and requires low costs for communication and computational as compared to other pertinent schemes.

INDEX TERMS Industrial Internet of Things (IoT), edge computing, blockchain, access control, key agreement, security.

I. INTRODUCTION

In recent years, the Internet of Things (IoT) has received a great attention across various fields, particularly in the Industrial Internet of Things (IIoT) environment. The assimilation of IoT and industry plays a significant role in building a large-scale smart automation industry. The IIoT endorse to provides scalable, cost effective, and secure system for manufacturing industrial goods. Recently, the applications of IIoT systems are escalating in various fields, such as smart manufacturing, transportation, aerospace, energy, logistics, healthcare and so on [1]. In addition, it is expected the market of IIoT will reach more than $110 billion USD by 2025 [2]. Recently, Pervasive Edge Computing (PEC) becomes a

The associate editor coordinating the review of this manuscript and approving it for publication was Chi-Yuan Chen.

very emerging computing standard. PEC consists of various heterogeneous mobile edge devices, such as ''smartphones'', ''tablets'', ''IoT smart devices'', ''gateway nodes'', ''edge devices'', and so on. The devices can then communicate with each other to sense, process the sensing information and also to build various applications at the network edge [3].

The rapid growth of IIoT leads to many security attacks, such as ''man-in-the-middle'', ''impersonation'', ''replay'' and ''privileged-insider'' attacks, which may cause serious damage to the IIoT system. Since most traditional and existing IIoT infrastructures are based on centralized system, they are expensive, inefficient and also vulnerable to a ''single-point failure''. Recently, combining blockchain technology and IoT-based security solutions achieves popularity among the researchers. Important features of blockchain (decentralization, tamper-proof, trustworthiness, traceability and immutability) provide more functionalities and greater help to the IIoT systems.

Blockchain is a distributed chain of structure on a decentralized Peer-to-Peer (P2P) network, which eliminates the requirement of centrally controlled system and allows the network entities to store the data in a distributed fashion. Considering the demand of large-scale IIoT systems, it becomes infeasible and inefficient to store the huge volumes of data in a traditional IIoT system. Therefore, we feel that a great essence in designing blockchain-based IIoT system for PEC. Thus, it should provide an efficient and robust solution to deal with the security requirements needed for PEC in IIoT environment. Since the information produced in the IIoT environment is strictly private and confidential, the information must not be leaked in public. Moreover, due to wireless communication happen among different entities in IIoT, an adversary should not be able to tamper with the sensitive data. Tampering of data may include intercepting, modifying, deleting or even inserting fake information during communication.

Integrating IIoT with blockchain technology in order to develop a ''secure, distributed, and stable blockchain IIoT network'' seems to be a natural way [4]. In fact, the integration of blockchain along with IIoT attracted a lot of interests among the stakeholders across industry and academia as well [5]. Due to drawbacks present in IIoT-based ''intelligent manufacturing system (IMS)'' and also the challenging problem associated to apply the blockchain in IMS, Zhang et al. [6] suggested to combine IIoT with the ''permissioned blockchain''. In this regard, they designed an efficient ''Manufacturing Blockchain of Things (MBCoT) architecture'' for the configuration of a secure, decentralized, and traceable IMS. Zhang et al. [7] also proposed a ''multi-access edge computing (MEC) enabled framework''. It helps in ''data security assurance'' and ''system latency performance'' improvement.

To deal with these issues, we represent a novel access control scheme. It allows secure communication among IoT smart devices and their relevant gateway nodes through the designed access control process. It also provides secure communication among the gateway nodes and the connected edge servers through the designed key management process. The secure transactions are then transformed into various blocks, and addition of those blocks are done through the ''Practical Byzantine Fault Tolerance (PBFT)'' introduced by Castro and Liskov [8]. It is done by a group of P2P edge servers network in the private blockchain.

A. MOTIVATION

In IIoT environment, there are various types of applications connected with the system and they integrate large-scale discrete heterogeneous data. Such data can be from the smart sensor data, health care data, traffic data, environmental monitoring data, and industrial manufacturing data. In some smart energy industries, sensors, machines, and actuators collect huge amount of data such as energy, air quality, fault and resource prediction, and product planning from various locations. It further produces large data and enforce a huge amount of processing time to store the data in traditional centralized system. Moreover, in chemical industry, there is an extensive amount of critical data, such as reactivity of a catalyst in different temperature and air pressure conditions, results after the chemicals reactions. In such scenario, inefficiency of IIoT system can seriously damage the productivity of the industry.

With the help of the cloud computing upgradation, IoT platform can process information in a traditional manner and transform the information into the real time actions. While the cloud storage becomes an important role in an IoT or IIoT environment, however there are issues related to threat of data, transparency and privacy preservation. This demands that we require to integrate the blockchain technology with the industrial IoT applications. Since the blockchain helps in providing the trusted sharing services where the reliable information and data can be retrieved, the data (information) can be then traceable. At the same time, the blockchain is also immutable; thus it enhances the security as well. Therefore, integration of decentralized blockchain in IIoT system can enable better efficiency, transparency and guarantee security solutions.

B. RELATED WORK

In recent years, ''access control and authentication'' are widely-used two main security mechanisms in providing security in IoT-enabled environments [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20].

1) NONBLOCKCHAIN-BASED SCHEMES

Li et al. [21] proposed an access control method in an ''Industrial Wireless Sensor Network (IWSN)'' environment. Their scheme permits a user to authorize, revoke, and authenticate for accessing real time information inside IWSN. Though their protocol supports both public verifiability and ciphertext authenticity, but it is impractical because of heavy computational overheads due to usage of the costly bilinear pairing operations.

Bilal and Kang [22] also designed an authentication approach in WSN deployment tailored to the IoT environment. In their protocol, a sensor node can establish multiple concurrent sessions to access information securely from other sensor nodes. Unfortunately, their approach is vulnerable to "parallel-session hijacking attack".

Xue et al. [23] suggested an access control mechanism for a smart home environment. Their scheme allows "authentication", "secure information access", and "unified storage provision" at the same time. However, the primary drawback related to this approach is that it does not provide "key agreement". Moreover, their scheme is vulnerable to "Ephemeral Secret Leakage (ESL) attack" under the CK-adversary model mentioned in the threat model (see Section I-B).

Li et al. [24] presented a three-factor user authentication scheme for IIoT environment. Unfortunately, their scheme fails to provide forward security and mobile device loss attack. Luo et al. [25] designed another access control mechanism for WSN-based IoT environment. Since their scheme is based on the identity based cryptographic technique, it is obviously heavy in computation due to costly bilinear pairing operations.

Li et al. [26] designed an elliptic curve cryptography (ECC)-based authentication scheme for IIoT which preserves privacy of the user and gateway nodes, and also provides wrong password detection mechanism quickly. Zeng et al. [27] designed an "anonymous user authentication (E-AUA)" protocol for both users and servers in an IoT environment. E-AUA uses multi-server environment to provide better services and also to overcome network congestion. Their scheme is also computationally expensive as costly bilinear pairing operations are applied. Moreover, their scheme is susceptible to "offline password guessing", "privileged-insider", and "server secret key leakage" attacks as mentioned in [12].

Esfahani et al. [28] designed an authentication protocol for IIoT with low computational cost which is based on the lightweight primitives like one-way hash function and XOR operations. However, their scheme requires to store secret authentication information on an authentication server, which may endanger a single point of failure. Garg et al. [29] proposed another lightweight ECC based authentication scheme for IoT based Industry 4.0 application. Though their scheme requires less computation cost, it does not resist against IoT smart device impersonation attack.

Zhang et al. [30] introduced a privacy preserving based CP-ABE scheme that supports authority verification without any privacy leakage which provides constant size private keys with short ciphertexts. It is also shown that the selective security under the "Decisional n-Bilinear Diffie-Hellman Exponent (n-BDHE)" computational problem with decisional linear assumption, is achieved in this scheme.

Xu et al. [31] illustrated a framework for privacy-preserving ABAC system, which assures the security and privacy of the outsourced users' data stored in "Cloud Service Provider (CSP)". The framework also supports secure de-duplication which helps to eliminate redundant encrypted data in the CSP with decent communication costs. Tian et al. [32] introduced an ABE full privacy protection (ABE-FPP) scheme based on three stages; 1) key generation, 2) access control, and 3) partial decryption. It provides policy hidden strategy, known as hybrid-verification strategy, that reveals only attribute names and also is able to hide its values to preserve privacy during partial decryption.

Later, Gupta et al. [33] tried to address the access control problems in the "intelligent transportation system (ITS)" ecosystem by proposing an ABAC system. Their system uses the fine-grained policies with individualized privacy choice in order to grant/deny different activities in the smart entities.

Han et al. [34] discussed the "role-based access control (RBAC)" that relies on the analysis using role-permissions matrices and also the implied concept of lattices. They evaluated their methodology by applying it to other substantial practical open-source systems, such as a) MediaWiki, b) Moodle, c) Joomla, and d) WordPress.

Garg et al. [29] suggested an authentication protocol for IoT-enabled Industry 4.0 enviroment that uses "elliptic curve cryptography (ECC)", "physically unclonable functions (PUFs)" and "hashing function" operations. However, their scheme does not support "session key security under the CK-adversary model", "dynamic sensor node addition phase" and "blockchain-based solution".

Amoon et al. [35] designed a "role-based reputed access control (RRAC)" scheme for protecting malicious attacks in an IoT system. Their scheme achieves two types of features, where it internally provides an "adaptive certificate based authentication" between users and resources, and it also externally trusts user communication. However, the role of IoT devices is determined separately based on reputation derived by the service provider (SP). In this scheme, precision of reputation is achieved by eliminating untrusted devices that are based on false reputation.

2) BLOCKCHAIN-BASED SCHEMES

Lin et al. [36] proposed a blockchain-based secure access control protocol (BSeIn) for industry 4.0 which provides essential security features, such as "authentication", "auditability", and "confidentiality". Moreover, their scheme applies costly bilinear pairing operations that substantially increase the computational overheads. Ren et al. [37] designed a "blockchain-based access control scheme for edge based IIoT". In their scheme, two entities make the session key based on short and long terms secrets, and as a result, their scheme is secure against ESL attack. Since the timestamp is not applied in their scheme, a strong replay attack protection is not provided.

Yu et al. [38] introduced a blockchain-based IoT application compatible with the "attribute-based encryption (ABE)", where the fine-grained access control is used for attributes updation. In addition, they introduced a verification scheme and showed their solution outperforms in searching complexity and the system revokes the members when there is a direct data leakage. However, Gao et al. [39] proposed trustworthy "Ciphertext-Policy Attribute-Based Encryption (CP-ABE)" scheme using ciphertext-policy and attribute hiding access policy with the help of blockchain technology. They used "homomorphic ElGamal cryptosystem" in order to assure the privacy of the attributes.

Zhang et al. [40] proposed an "attribute-based access control (ABAC) framework for smart city application" using blockchain smart contract technology. Their scheme consists of a policy management using private Ethereum smart contracts for maintaining policies in ABAC. They computed the cost of gas consumption on Ethereum platform.

Nakamura et al. [41] proposed "Capability-Based Access Control (CapBAC)" scheme which stores and manages the capability tokens with local Ethereum-based implementation. However, their scheme fails to resist potential attacks. Moreover, Liu et al. [42] presented a CapBAC system using the blockchain technology to regulate the "dynamic identities (DIDs)" for different identities and access rights granting to IoT devices.

In 2023, Yu et al. [43] suggested an access control mechanism using the blockchain for an IoT environment. Their approach relies on the Attribute-Based Access Control (ABAC) model. In their scheme, use of the use of decentralized ABAC model helps for secure decision-making in order to control variables that ensure a fine-grained access control approach.

In 2023, Vangala et al. [44] suggested an "efficient blockchain-enabled authenticated key agreement scheme for mobile vehicles-assisted precision agricultural IoT networks, called AgroMobiBlock". The novelty lies in AgroMobiBlock is that it uses the "elliptic curve operations on an active hybrid blockchain over mobile farming vehicles with low computation and communication costs".

In 2023, the authors in [45] highlighted various security challenges that are faced for the large IoT based infrastructures like smart cities. Next, they designed a dynamic solution for mitigating the challenges in large IoT based infrastructures with the help of a zero-trust and Attribute-Based Access Control (ABAC) policy, and the blockchain technology.

3) COMPARATIVE ANALYSIS ON VARIOUS FEATURES WITH EXISTING APPROACHES

In Table 1, we have provided a comparative analysis of the proposed framework with the state of art existing solutions with respect to various "cryptographic techniques, advantages and limitations" in an IoT environment. The literature study from the existing schemes shows that the existing schemes are either lacking to meet appropriate security requirements or they do not offer blockchain-based solutions in IIoT environment. Moreover, the operational costs due to bilinear pairings make the schemes inefficient and thus, it may not be viable in large scale IIoT system. The recent schemes in "role-based access control (RBAC)", "attribute-based access control (ABAC)", and "capability-based access control (CapBAC)" are mostly centralized cloud-based solutions and they do not provide the appropriate usability of access control with blockchain-based solution in IIoT system. On the other side, the proposed solution in this article offers better security features and more functionality features including protection of session key security under the CK-adversary model [46] and also the blockchain-based solution. Furthermore, the proposed scheme provides "voting-based consensus for verification and addition of a block in blockchain" and resist from possible attacks in blockchain such as transaction privacy leakage, selfish mining attack, balance attack and Sybil attack. Additionally, the proposed scheme is efficient in communication as well as computation as compared to other considered existing competing schemes. Notably, in the proposed scheme (PBACS-PECIIoT), the registration credentials obtained by a smart device (SD_i) and the gateway node (GN_j) are fetched from the Blockchain during the access control phase for authentication and key agreement purposes. Additionally, the registration credentials stored in the blockchain center (BC) are also fetched by an edge server for key management purpose with its gateway node.

C. RESEARCH CONTRIBUTIONS

The key contributions towards this work are mentioned below.

- We propose a novel "private blockchain-envisioned access control scheme for Pervasive Edge Computing (PEC) in IIoT environment, called PBACS-PECIIoT". The purpose behind applying the private blockchain is that the transactions and registration credentials of the entities related to IIoT are confidential and private.
- In the proposed PBACS-PECIIoT, registration credentials obtained by a smart device (SD_i) and the gateway node (GN_j) are fetched from the Blockchain during the access control phase for authentication and key agreement purposes. Additionally, it is also worth to notice that the registration credentials stored in the blockchain center (BC) are fetched by an edge server for key management purpose with its gateway node.
- After collecting the information securely from the deployed IoT smart devices by their respective gateway node(s), the information is securely delivered to the edge servers by their associated gateway nodes in form of transactions. The edge servers are then responsible for building the blocks, verifying and adding them in the private blockchain with the help of the proposed voting-

TABLE 1. Cryptographic techniques, advantages and limitations of existing authentication/access control schemes in IoT environment.

Scheme	Cryptographic Techniques	Advantages	Drawbacks/Limitations	Blockchain Usage
Li *et al.* [21]	* Elliptic Curve Cryptography (ECC) * Bilinear pairings * Hash functions * Modular exponentiation	* A user is allowed to authorize, revoke, and authenticate for accessing real time information inside IWSN * Signcryption	* Heavy computational overheads due to bilinear pairing operations * Does not support blockchain security solution	–
Bilal and Kang [22]	* Encryption/decryption * Hash function	* Mutual authentication * Key establishment * Establishment of multiple concurrent sessions among sensor nodes	* Vulnerable to parallel-session hijacking attack * Does not support blockchain solution	–
Xue *et al.* [23]	* Hash functions * Signcryptions * Encryption/decryption	* Authentication * Secure information access * Unified storage provision	* Does not provide "key agreement * Vulnerable to "Ephemeral Secret Leakage (ESL) attack under CK-adversary model	Passive blockchain
Li *et al.* [26]	* ECC * One-way hash function * Fuzzy extractor for biometric verification	* Mutual authentication * Session key agreement	* Vulnerable to "Ephemeral Secret Leakage (ESL) attack under CK-adversary model * Does not support security blockchain solution	–
Luo *et al.* [25]	* ECC * One-way hash function * Cross domain heterogeneous signcryption (CDHSC) * Bilinear pairings	* Authentication * Session key agreement	* Does not support dynamic sensor node addition phase * Does not support blockchain solution * Computationally costly due to bilinear pairing operations	–
Lin *et al.* [36]	* One-way hash function *Hashed message authentication code (HMAC) * Modular exponentiation	* Mutual authentication * Session key agreement * User anonymity * Supports blockchain solution	* Computationally costly	Passive blockchain
Zeng *et al.* [27]	* ECC * Bilinear pairings	* Online login and authentication * Password change phase	* Insecure against offline password guessing * Vulnerable to privileged-insider attack * Vulnerable to server secret key leakage * Does not support dynamic IoT device addition phase * Does not support blockchain solution	–
Ren *et al.* [37]	* ECC * One-way hash functions	* Mutual authentication * Session key agreement * Supports blockchain solution	* Vulnerable to replay attack * Does not support dynamic IoT device addition phase	Passive blockchain
Esfahani *et al.* [28]	* One-way hash function * Bitwise XOR operation	* Mutual authentication * Session key agreement	* Single point of failure * Does not support dynamic IoT device addition phase * Does not support blockchain solution	–
Garg *et al.* [29]	* ECC * Physically Unclonable Functions (PUFs)	* Mutual authentication * Session key agreement	* Vulnerable to IoT smart device impersonation attack * Does not support dynamic IoT device addition phase * Does not support blockchain solution	–
Li *et al.* [24]	* ECC * One-way hash function * Fuzzy extractor for biometric verification * Encryption/decryption	* Mutual authentication * Session key agreement	* Does not provide forward security * Insecure against mobile device loss attack * Does not support security blockchain solution	–
Proposed (PBACS-PECIIoT)	* ECC * One-way hash function * Symmetric key encryption	* Mutual authentication * Session key agreement * Supports blockchain solution	* Implementation of real testbed experiments for access control and key management parts	Active hybrid blockchain

based "Practical Byzantine Fault Tolerance (PBFT)" algorithm [8]. The local ledgers are maintained by the edge servers in the blockchain center.

- A detailed security analysis including the formal security verification has been conducted. It demonstrates that PBACS-PECIIoT is secure against a number of potential attacks against passive/active adversaries.
- The "real testbed experiments for various cryptographic primitives with the help of widely-accepted Multiprecision Integer and Rational Arithmetic Cryptographic Library (MIRACL)" [47] have been performed under both server and Raspberry PI 3 platforms. These testbed experiments measure the computational time for the primitives with respect to these

platforms. Moreover, a detailed comparative analysis among PBACS-PECIIoT and other related existing schemes has been performed. It shows the effectiveness and robustness of PBACS-PECIIoT over other schemes.
- The proposed PBACS-PECIIoT is also implemented through blockchain simulation study in order to measure its performance as well as computational time.

D. EVALUATION METRICS

The following evaluation metrics are crucial in the design of an access control scheme in an IIoT environment that used the blockchain technology:

- *Scalability:* The designed access control scheme should support a large number of IoT devices. As a result, it must be also flexible enough against a substantial increase in the network size even after the initial deployment of the IoT devices nodes in the network. This demands for dynamic IoT devices deployment after the initial deployment.
- *Use of active hybrid blockchain*: In an access control scheme, the blockchain technology should not only be used for storing the authenticated data in the blockchain, but also be used during the access control procedure as well to retrieve the registration credentials of the entities from the blockchain as well.
- *Storage cost:* The amount of memory needed for storing the security credentials particularly in the IoT devices (which are typically resource limited) should be kept in minimum.
- *Communication cost:* The number of messages that need to be exchanged during the authentication procedure in the designed access control scheme should be less as possible.
- *Computational cost:* It is measured as the amount of processor cycles needed to authenticate and establish a shared session key between two communicating entities in the IoT network. It needs to be minimum particularly for the resource limited IoT devices.
- *Resilience against physical IoT device capture attack:* Sometimes, the IoT devices can not be monitored always 24×7. Hence, an adversary $\mathcal{A}$ can physically capture an IoT device and extract all the information stored in its memory using the "power analysis attacks" as mentioned in [48] (see in the threat model discussed in Section II-B). The resilience against IoT device capture attack is measured by "estimating the fraction of total secure communications that are compromised by a capture of n_c devices *not including* the communication in which the compromised devices are directly involved" as in [49]. Let us say $P_e(n_c)$ will be the "fraction of total secure communications compromised after capturing n_c IoT devices by the adversary $\mathcal{A}$ in the IoT network". Now, if $P_e(n_c) = 0$, an access control scheme will be called as *unconditionally secure against IoT device capture* or *perfectly resilience against IoT device capture*.
- *Resilience against general attacks*: In an IoT network, the attacks like "replay", "Man-in-the-Middle (MiTM)", "impersonation", and "privileged-insider" attacks should be resisted in an access control scheme like other networks. Moreover, a more important attack, known as "Ephemeral Secret Leakage (ESL)" attack should be protected in the aspect of the session key security.
- *Resilience against blockchain-related attacks*: In an access control scheme that uses the blockchain technology, the blockchain related attacks, such as "transaction privacy leakage", "selfish mining", "balance" and "Sybil" attacks should be also protected against an adversary.

E. PAPER ORGANIZATION

In the next section, we discuss the system model by considering both the network and threat models. In Section III, the detailed phase-wise discussion of various phases related to PBACS-PECIIoT is provided. The security analysis on PBACS-PECIIoT is provided in sections IV and V. In Section VI, we perform the testbed experiments with the help of widely-accepted "Multiprecision Integer and Rational Arithmetic Cryptographic Library (MIRACL)" [47]. Next, a detailed comparative study among PBACS-PECIIoT and other existing relevant schemes is provided in Section VII. The blockchain implementation is shown on the proposed PBACS-PECIIoT in Section VIII. Finally, the paper is ended with concluding remarks in Section IX.

II. SYSTEM MODEL

In this section, the network as well as threat models used in the proposed scheme (PBACS-PECIIoT) are discussed.

A. NETWORK MODEL

The network model used in the proposed PBACS-PECIIoT is shown in Figure 1. The model shows different types of IIoT applications, such as mobile, car, aerospace, and food manufacturing industry.

Various smart IoT devices are attached with each unit of an industry, and all the smart devices, say $(SD_i| \ i = 1, 2, 3, \ldots, n_{sd})$ are connected with the associated gateway node(s), say $(GN_j| \ j = 1, 2, 3, \ldots, n_{gn})$. Each GN_j is connected with an edge server, say $(ES_l|l = 1, 2, 3, \ldots, n_{es})$. The registration of all the entities $(SD_i, \ GN_j, \ ES_l)$ is executed by a trusted registration authority, say $(RA_k \ |k = 1, 2, 3, \ldots, n_{ra})$ for a particular application. Here, n_{sd}, n_{gn}, n_{es} and n_{ra} represent the number of IoT smart devices, gateway nodes, edge servers and RAs, respectively. All the registered ES_l form a P2P edge servers network, which is also called as the blockchain center. An edge server, being a leader node, say ES_l, runs a consensus algorithm for creating, verifying, adding, and also mining the blocks in their *local ledgers* of the blockchain center.

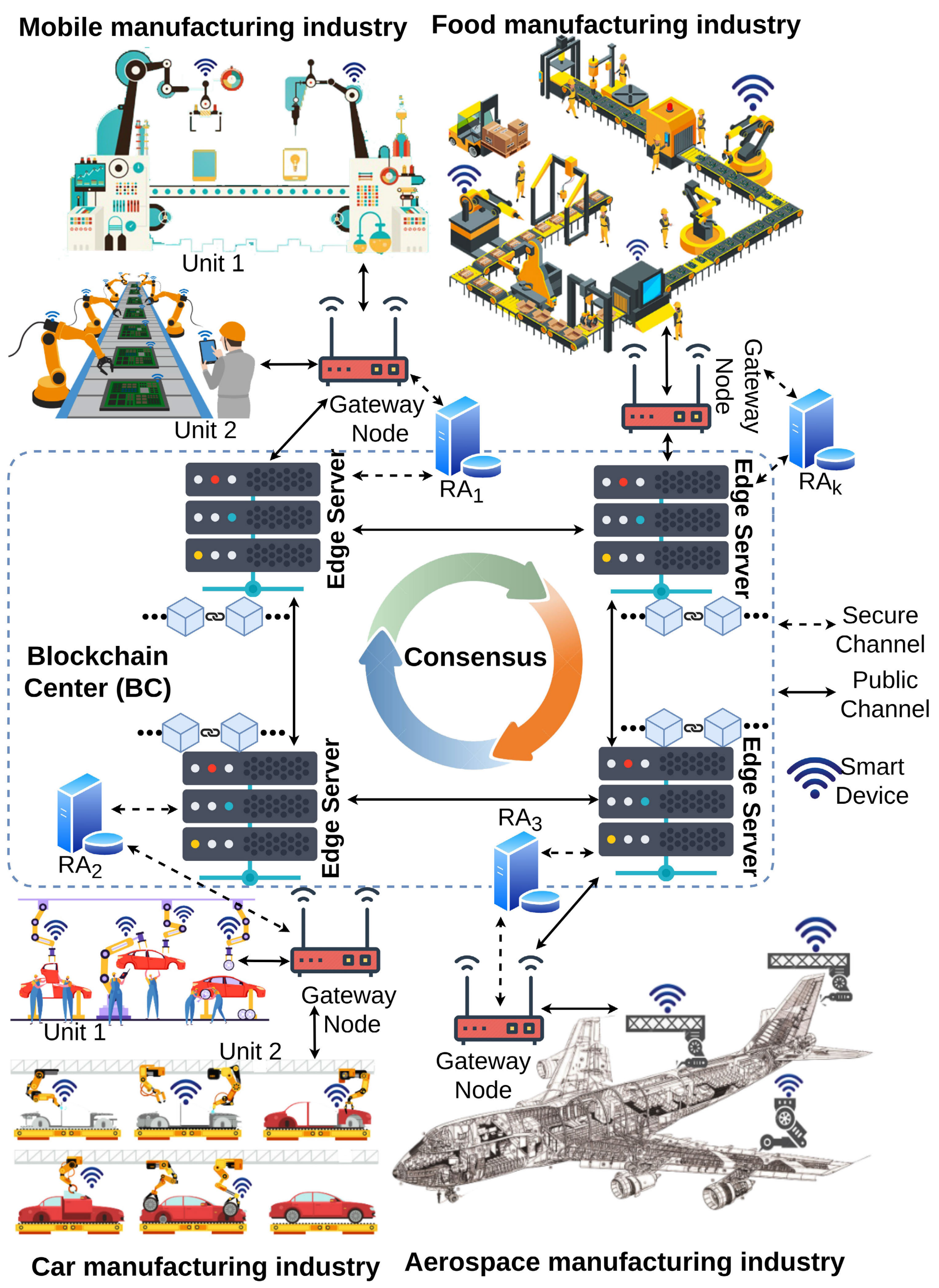


FIGURE 1. Blockchain-envisioned edge-based IIoT environment.

B. THREAT MODEL

The involved entities in an "IIoT environment" need to communicate over insecure channels. Therefore, an adversary $\mathcal{A}$ can take an opportunity to manipulate/compromise the data exchanged between them. In this paper, we adapt the broadly-accepted "Dolev-Yao threat model (known as DY model)" [50]. Under the DY model, $\mathcal{A}$ "not only eavesdrops, but can also modify, delete and insert fake information during the communication among the entities". In addition, we also adapt the widely-known "Canetti and Krawczyk's model (CK-adversary model)" [46] which is presently a *de facto* threat model as compared to the DY model. Under the "CK-adversary model", $\mathcal{A}$ can compromise the "secret credentials shared between two communicating parties. This results the adversary $\mathcal{A}$ to compromise the past or future established session keys between the communicating parties by means of compromising the session states and session keys".

We assume that end-point entities (IoT smart devices) are not trusted, whereas the gateway nodes and edge servers are semi-trusted and the registration authorities are fully trusted. Since it may not be possible to monitor the IoT smart devices in 24 $\times$ 7, a physical theft of some IoT smart devices by $\mathcal{A}$ may happen. It may then lead to compromise the secret credentials stored in the captured devices using some sophisticated "power analysis attacks" as mentioned in [48].

III. THE PROPOSED SCHEME

In this section, different phases relevant to the proposed private blockchain-envisioned access control scheme for edge-based IIoT environment, PBACS-PECIIoT, has been designed.

The proposed PBACS-PECIIoT has various phases, like *registration*, *access control*, *key management*, and *block creation, verification and addition in blockchain*. In Figure 2, we have illustrated the complete process in PBACS-PECIIoT. Note that in this paper, we consider the access control that mainly consists of the following two tasks [51], [52]:

Task 1 (Node authentication): This task permits that the newly deployed IoT smart devices and their nearby accessible gateway nodes must authenticate themselves to their neighbor nodes for proving the fact that they are genuinely deployed nodes in the network, and they can also access the network for services.

Task 2 (Key agreement): This task is needed for the nodes to establish secret (session) keys with the neighbor nodes (for instance, between an "IoT smart device" and its associated "gateway node") to assure secure communication after the node authentication process is completed.

The idea behind the design of the proposed scheme is to mutually authenticate two communicating entities through the access control mechanism. It helps in establishing the secret session keys between the authorized entities in the IoT network so that they can secure communicate among each other for secure data delivery. In addition, the key management process between a gateway node and its associate edge server helps in secure communication among them.

Another interesting novelty in the proposed scheme is that as compared to other existing schemes in the literature, the registration credentials obtained by a smart device (SD_i) and the gateway node (GN_j) are obtained from the Blockchain during the access control phase for authentication and key agreement purposes of the proposed PBACS-PECIIoT. Moreover, the registration credentials stored in the blockchain center (BC) are also extracted by an edge server for key management purpose with its gateway node. The existing works on authentication in IoT networks use the passive usage of blockchains with high costs. However, in the present scheme (PBACS-PECIIoT), we have not only utilized the passive blockchain for the secure storage purpose, but also active blockchain during the retrieval of registration credentials during the registration processes. As a result, the active hybrid blockchain has been utilized for strong security in the proposed scheme.

The deployed IoT smart devices first send the messages encrypted with their established session keys during the "access control phase" in Section III-B to their respective gateway node(s). The gateway nodes then send the information encrypted with their secret keys established during the"key management phase" in Section III-C to their respective edge servers. An in-charge edge server is responsible to create a block containing the encrypted transactions of information received from the gateway node(s) or IoT smart device(s) for a particular application.

Since PBACS-PECIIoT makes use of current system timestamps for safeguarding replay attacks, all the communicating entities, like "IoT smart devices", "gateway nodes" and "edge servers", are synchronized with their clocks. It is a widely accepted presumption applied in "different existing authentication and access control approaches under individual networking scenarios" [53], [54]. The list of symbols tabulated in Table 2 are utilized in describing and analyzing the proposed PBACS-PECIIoT. We have provided this notation table for better presentation and understanding of the proposed PBACS-PECIIoT as well. In the proposed scheme, we have used a "non-singular elliptic curve $E_q(\alpha, \beta) : y^2 = x^3 + \alpha x + \beta \pmod q$ over a finite (Galois) field $GF(q)$, where $\alpha, \beta \in Z_q = \{0, 1, 2, \ldots, q-1\}$ are constants with $4\alpha^3 + 27\beta^2 \neq 0 \pmod q$. In an elliptic curve, there are two types of operations are supported: 1) point addition and 2) scalar multiplication. If $P = (x_P, y_P)$ and $Q = (x_Q, y_Q)$ be two points in $E_q(\alpha, \beta)$, then $R = (x_R, y_R) = P + Q$ is calculated by the following rule [55]:

$$x_R = (\mu^2 - x_P - x_Q) \pmod p$$
$$y_R = (\mu(x_P - x_R) - y_P) \pmod p$$

where $\mu = \begin{cases} \frac{y_Q - y_P}{x_Q - x_P} \pmod p, \text{ if } P \neq -Q \\ \frac{3x_P^2 + a}{2y_P} \pmod p, \text{ if } P = Q. \end{cases}$

The case $P = Q$ is often referred as doubling the point, and it is represented as $2.P$. In particular, $k \cdot P = P + P + \cdots + P$ (k times), is called elliptic curve point multiplication, where $k \in Z_q^* = \{1, 2, \cdots, q-1\}$.

A. REGISTRATION PHASE

During registration process of all the communicating entities, like "IoT smart devices", "gateway nodes" and "edge servers", each registration authority RA_k ($k = 1, 2, \ldots, n_{ra}$) selects the following system parameters. First of all, each RA_k will pick a large prime q and a "non-singular elliptic curve $E_q(\alpha, \beta) : y^2 = x^3 + \alpha x + \beta \pmod q$ over a finite (Galois) field $GF(q)$ with two constants $\alpha, \beta \in Z_q$ such that the Elliptic Curve Discrete Logarithm Problem (ECDLP) becomes intractable due to sufficiently chosen large prime q". For instance, to make ECDLP intractable, q should be chosen at least 160 bits such that 160-bit "Elliptic Curve Cryptography (ECC)" security remains same as that for an 1024-bit RSA public key cryptosystem [56]. In addition, each RA_k also selects a base point G_k corresponding to the chosen elliptic curve $E_q(\alpha, \beta)$ whose order will be as big as q, and a common collision resistant cryptographic hash function $h(\cdot)$ (for example, we can apply the Secure Hash Algorithm (SHA-256) hash function). Furthermore, each RA_k

TABLE 2. Notations and their meanings.

Symbol	Meaning
RA	Trusted registration authority
SD_i, RID_{SD_i}	i^{th} IoT smart device and its pseudo identity
GN_j, RID_{GN_j}	j^{th} gateway node and its pseudo identity
ES_l, RID_{ES_l}	l^{th} edge server and its pseudo identity
$n_{sd}, n_{ra}, n_{gn}, n_{es}$	Number of IoT smart devices, RAs, gateway nodes and edge servers, respectively
$h(\cdot)$	A collision-resistant cryptographic one-way hash function
q	A large prime number
$GF(q)$	Galois finite field over prime q
$E_q(\alpha, \beta)$	A non-singular elliptic curve: $y^2 = x^3 + \alpha x + \beta \pmod q$ over $GF(q)$ with $\alpha, \beta \in Z_q = \{0, 1, \cdots, q-1\}$
G_k	A base point in $E_q(\alpha, \beta)$
$P + Q$	Elliptic curve point addition of two points $P, Q \in E_q(\alpha, \beta)$,
$u \cdot G_k$	Elliptic curve point multiplication; $u \cdot G_k = G_k + G_k + \cdots G_k$ (u times), $G_k \in E_q(\alpha, \beta)$, $u \in Z_q^*$
$u * v$	Modular multiplication of elements $u, v \in Z_q$
(pr_X, Pub_X)	Signature private-public key pair of an entity X, where $Pub_X = pr_X \cdot G_k$
$E(\cdot)/D(\cdot)$	ECC encryption/decryption algorithm
TS_x	Current system timestamp generated by an entity X
ΔT	Maximum transmission delay associated with a message
$\|\|$, $\oplus$	Data concatenation and exclusive-OR operators, respectively

picks its own secret (private) master key mk_{RA_k} which is kept secret to itself, computes the respective public key $Pub_{RA_k} = mk_{RA_k} \cdot G$ and makes the system parameters $\{E_q(\alpha, \beta), G_k, h(\cdot), Pub_{RA_k}\}$ as public.

1) IoT SMART DEVICES REGISTRATION

This phase occurs in offline mode prior to deployment of the IoT smart devices in their respective deployment areas by the associated registration authority RA_k. Note that the private and public key pairs for the IoT smart devices are generated by the registration authority RA_k, and these are pre-installed in IoT devices' memory before placing them in the network.

For registering each deployed IoT smart device SD_i for a particular application of IIoT, the respective registration authority RA_k first selects a unique identity ID_{SD_i} and then computes the corresponding pseudo-identity $RID_{SD_i} = h(ID_{SD_i} || mk_{RA_k})$ and temporal credential $TC_{SD_i} = h(RID_{SD_i} || mk_{RA_k} || RTS_{SD_i} || pr_{SD_i})$ of SD_i, where the private key of each SD_i is a random secret $pr_{SD_i} \in Z_q^* = \{1, 2, \ldots, q-1\}$ and its public key is $Pub_{SD_i} = pr_{SD_i} \cdot G_k$, and RTS_{SD_i} is the registration timestamp of SD_i. The RA_k stores the information $\{RID_{SD_i}, pr_{SD_i}, Pub_{RA_k}\}$ into its secure memory prior to placement in IIoT application, and makes Pub_{SD_i} as public.

After that, the RA sends the registration related credentials $RegCred_{SD_i} = \{RID_{SD_i}, TC_{SD_i}, Pub_{SD_i}, E_q(\alpha, \beta), G_k\}$ to the blockchain center (BC) in the form of a transaction, say $Tx_{RegCred_{SD_i}} = \langle RID_{SD_i}, E_{Pub_{SD_i}}[RegCred_{SD_i}], ECDSA.Sign_{mk_{RA_k}}[RegCred_{SD_i}] \rangle$, where $E_{Pub_X}(\cdot)$ and $D_{pr_X}(\cdot)$ represent the "ECC-based encryption and decryption using the public key Pub_X and private key pr_X of an entity," respectively, and $ECDSA.Sign(\cdot)$ and $ECDSA.Ver(\cdot)$ denote the "elliptic curve digital signature algorithm (ECDSA)-based signature generation and verification methods," respectively.

RA_k deletes RID_{SD_i}, TC_{SD_i} and (pr_{SD_i}, Pub_{SD_i}) from its database for "security reasons in order to avoid privileged-insider attack". It is worth noticing that the registration credentials need not to be sent back to the IoT devices after the registration process, because the credentials are directly stored in the memory of the deployed smart devices as well as in the blockchain center prior to their placement in the network.

Remark 1: During the IoT smart devices registration process, an IoT device SD_i needs to store the registration credentials $\{RID_{SD_i}, pr_{SD_i}, Pub_{RA_k}\}$ in its memory. If we assume that a "random number", an "identity", a "one-way hash function (using SHA-256 hashing algorithm)", an "elliptic curve point $P \in E_q(\alpha, \beta)$" and a "timestamp" are 160, 160, 256, 320, and 32 bits, respectively, the storage cost for SD_i becomes $(256 + 160 + 320) = 736$ bits only. As a result, the proposed scheme is efficient in storage overhead particularly for the IoT smart devices, which are resource limited as compared to other nodes like gateway nodes and edge servers.

2) GATEWAY NODES REGISTRATION

To register a gateway node GN_j belonging to a particular IIoT application, its respective RA_k first picks the unique identity ID_{GN_j} and then computes its pseudo-identity $RID_{GN_j} = h(ID_{GN_j} || mk_{RA_k})$ and temporal credential $TC_{GN_j} = h(ID_{GN_j} || RTS_{GN_j} || mk_{RA_k})$ for GN_j, where RTS_{GN_j} is GN_j's registration time. Next, RA_k picks a "t-degree symmetric bivariate polynomial over the finite (Galois) field $GF(q)$ as $g_j(x, y) = \sum_{u=0}^{t} \sum_{v=0}^{t} a_{u,v} x^u y^v$, where the co-efficients

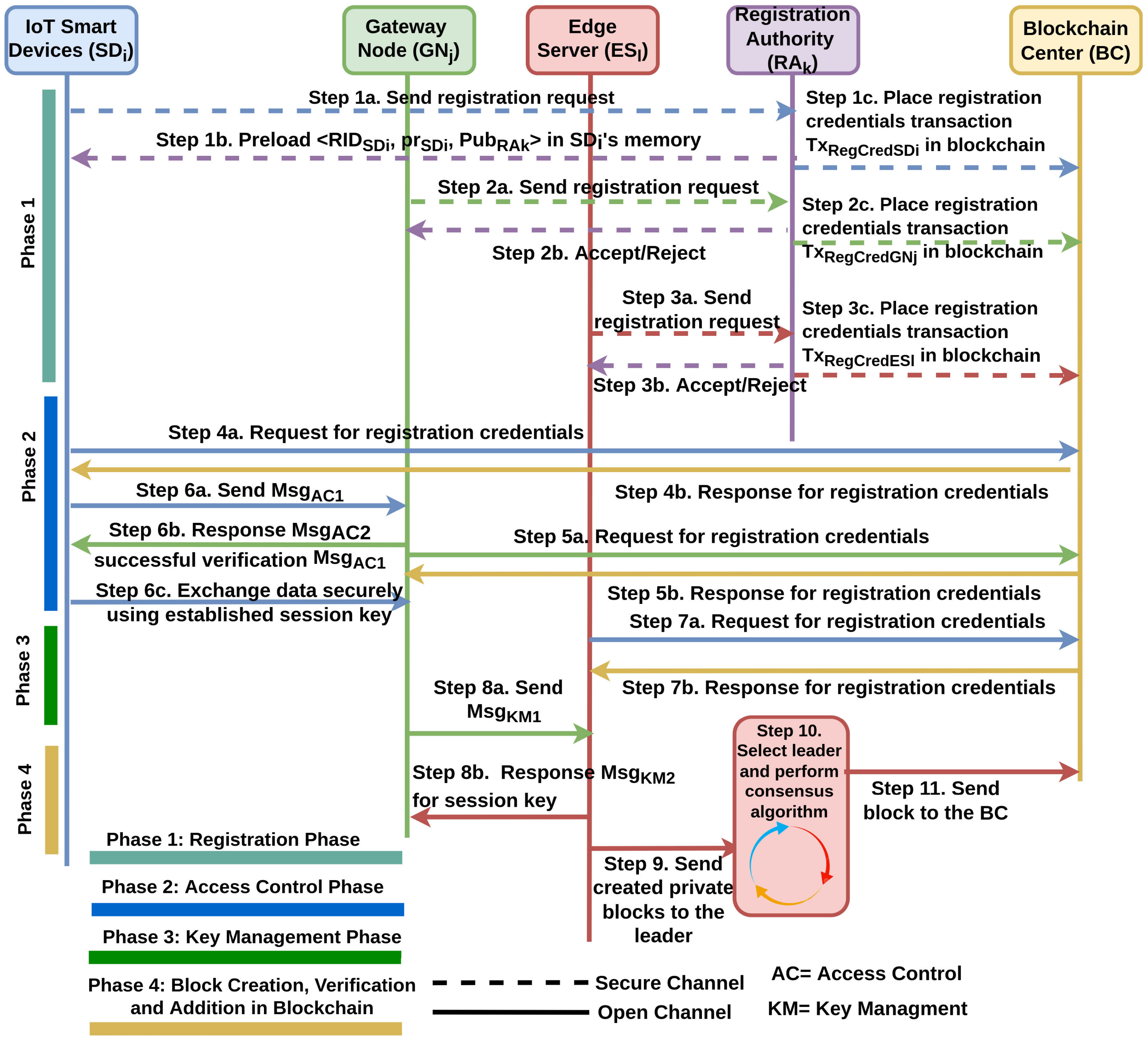

IoT Smart Devices (SD$_i$)
Gateway Node (GN$_j$)
Edge Server (ES$_l$)
Registration Authority (RA$_k$)
Blockchain Center (BC)
Phase 1
Phase 2
Phase 3
Phase 4
Step 1a. Send registration request
Step 1b. Preload <RID$_{SDi}$, pr$_{SDi}$, Pub$_{RAk}$> in SD$_i$'s memory
Step 1c. Place registration credentials transaction Tx$_{RegCredSDi}$ in blockchain
Step 2a. Send registration request
Step 2b. Accept/Reject
Step 2c. Place registration credentials transaction Tx$_{RegCredGNj}$ in blockchain
Step 3a. Send registration request
Step 3b. Accept/Reject
Step 3c. Place registration credentials transaction Tx$_{RegCredESl}$ in blockchain
Step 4a. Request for registration credentials
Step 4b. Response for registration credentials
Step 5a. Request for registration credentials
Step 5b. Response for registration credentials
Step 6a. Send Msg$_{AC1}$
Step 6b. Response Msg$_{AC2}$ successful verification Msg$_{AC1}$
Step 6c. Exchange data securely using established session key
Step 7a. Request for registration credentials
Step 7b. Response for registration credentials
Step 8a. Send Msg$_{KM1}$
Step 8b. Response Msg$_{KM2}$ for session key
Step 9. Send created private blocks to the leader
Step 10. Select leader and perform consensus algorithm
Step 11. Send block to the BC
Phase 1: Registration Phase
Phase 2: Access Control Phase
Phase 3: Key Management Phase
Phase 4: Block Creation, Verification and Addition in Blockchain
Secure Channel
Open Channel
AC= Access Control
KM= Key Managment

FIGURE 2. Illustration of complete process in PBACS-PECIIoT.

$a_{u,v}$ are from Z_q, $g_j(x, y) = g_j(y, x)$, and $t \gg n_{gn}$ and $t \gg n_{es}$", as in Blundo et al.'s scheme [57]. Furthermore, RA_k calculates the polynomial share $g_j(RID_{GN_j}, y) = \sum_{u=0}^{t} \sum_{v=0}^{t} a_{u,v}(RID_{GN_j})^u y^v$ over $GF(q)$ and sends the registration credential $\{RID_{GN_j}\}$ to GN_j via a secure channel (for example, in person).

After receiving the registration credentials from RA_k, GN_j picks its own random secret (private) key $pr_{GN_j} \in Z_q^*$, computes the respective public key $Pub_{GN_j} = pr_{GN_j} \cdot G_k$, stores the private key pr_{GN_j} in its secure database and publishes the public key Pub_{GN_j}. Next, the RA_k sends the registration credentials $RegCred_{GN_j} = \{RID_{GN_j}, TC_{GN_j}, g_j(RID_{GN_j}, y), E_q(\alpha, \beta), G_k, \{(RID_{SD_i}, Pub_{SD_i})\}, Pub_{GN_j}\}$ to the blockchain center (BC) in the form of a transaction, say $Tx_{RegCred_{GN_j}} = \langle RID_{GN_j}, E_{Pub_{GN_j}}[RegCred_{GN_j}], ECDSA.Sign_{mk_{RA_k}}[RegCred_{GN_j}]\rangle$. Note that only for the IoT smart devices SD_i that are associated with GN_j in a particular IIoT application, $\{(RID_{SD_i}, Pub_{SD_i})\}$ are available to GN_j. RA_k also deletes RID_{GN_j} and TC_{GN_j} from its database for security reasons in order to avoid "privileged-insider attack", and stores Pub_{GN_j} in each associated SD_i's memory. Finally, GN_j stores the credentials $\{RID_{GN_j}, pr_{GN_j}\}$ in its secure database.

3) EDGE SERVERS REGISTRATION

To register an edge server ES_l belonging to one or more GN_j for a particular IIoT application, the in-charge RA_k picks a unique identity ID_{ES_l} for ES_l and computes the pseudo-identity $RID_{ES_l} = h(mk_{RA_k} || ID_{ES_l})$ and the polynomial share $g_j(RID_{ES_l}, y) = \sum_{u=0}^{t}\sum_{v=0}^{t} a_{u,v}(RID_{ES_l})^u y^v$ over $GF(q)$. It is worth noticing that $g_j(x, y)$ is the common polynomial shared between GN_j and ES_l. After that RA_k sends the registration credentials $\{RID_{ES_l}\}$ to ES_l via secure channel.

Once the registration credentials are received by ES_l from RA_k, ES_l picks its own random private key $pr_{ES_l} \in Z_q^*$, calculates the corresponding public key $Pub_{ES_l} = pr_{ES_l} \cdot G_k$, and publishes Pub_{ES_l} as public. Here, the polynomial $g_j(x, y)$ is used to setup a symmetric secret key between the "gateway node GN_j" and its associated "edge server ES_l", which is further utilized in establishing the session key SK_{ES_l,GN_j} (SK_{GN_j,ES_l}) between them for secret communications (see Section III-C).

The RA sends the registration credentials $RegCred_{ES_l} = \{RID_{ES_l},\ g_j(RID_{ES_l}, y),\ TC_{ES_l},\ Pub_{ES_l},\ E_q(\alpha, \beta),\ G_k\}$ to the blockchain center (BC) in the form of a transaction, say $Tx_{RegCred_{ES_l}} = \langle RID_{ES_l},\ E_{Pub_{ES_l}}[RegCred_{ES_l}],$ $ECDSA.Sign_{mk_{RA_k}}[RegCred_{ES_l}]\rangle$. Finally, ES_l needs to store the credentials $\{RID_{ES_l}, pr_{ES_l}\}$ in its secure database.

Remark 2: It is noted that the IoT smart devices registration phase occurs in offline mode prior to deployment of the IoT devices in their respective deployment areas by the associated RA_k. In addition, the registration of the gateway nodes GN_j and the edge servers ES_l are executed in secure channels by the RA_k. As a result, there is no possibility of the impersonation attacks by an adversary (including the insider attacker) at the device/gateway/edge server registration phases becuase the encrypted registration credentials along with their signatures are placed into the blockchain.

B. ACCESS CONTROL PHASE

It is done between a "registered IoT smart device (SD_i)" and its respective "gateway node (GN_j)" for a particular application in IIoT. This phase helps to perform a "mutual authentication and session key establishment between SD_i and GN_j". Before initiating the access control process, the SD_i and GN_j need to obtain the registration credentials that are already stored in the blockchain center (BC). Note that this is executed only once because the registration credentials obtained from the BC can be stored in the secure databases of both SD_i and GN_j. For this purpose, the following steps are involved:

- *Registration credentials obtained by smart device (SD_i):* SD_i first sends a request message $RegCredReq_{SD_i} = \{RID_{SD_i}\}$ to the BC over open channel for obtaining its registration credentials. After receiving the request, the BC checks RID_{SD_i} and fetches the transaction $Tx_{RegCred_{SD_i}} = \langle RID_{SD_i},$ $E_{Pub_{SD_i}}[RegCred_{SD_i}],\ ECDSA.Sign_{mk_{RA_k}}[RegCred_{SD_i}]\rangle$ and sends it to SD_i over public channel. SD_i upon receiving $Tx_{RegCred_{SD_i}}$, decrypts $E_{Pub_{SD_i}}[RegCred_{SD_i}]$ using the public key Pub_{RA_k} of the associated RA_k to extract $RegCred_{SD_i} = \{RID_{SD_i}, TC_{SD_i}, Pub_{SD_i}, E_q(\alpha, \beta), G_k\}$. Now, if the decrypted RID_{SD_i} matches with its received version, SD_i further validates the signature $ECDSA.Sign_{mk_{RA_k}}[RegCred_{SD_i}]$ by applying the $ECDSA.Ver(\cdot)$ algorithm using the RA_k's public key Pub_{RA_k}. If the signature is valid, SD_i then only stores $RegCred_{SD_i}$ in its memory for the mutual authentication and key establishment purpose.
- *Registration credentials obtained by gateway node (GN_j):* GN_j also sends a request message $RegCredReq_{GN_j} = \{RID_{GN_j}\}$ for obtaining the registration credentials to the BC over open channel. Once the request is processed by the BC, the BC checks RID_{GN_j}, fetches the transaction $Tx_{RegCred_{GN_j}} = \langle RID_{GN_j},\ E_{Pub_{GN_j}}[RegCred_{GN_j}],$ $ECDSA.Sign_{mk_{RA_k}}[RegCred_{GN_j}]\rangle$ corresponding to RID_{GN_j} and sends it to GN_j over public channel. Moreover, GN_j upon receiving $Tx_{RegCred_{GN_j}}$, decrypts $E_{Pub_{GN_j}}[RegCred_{GN_j}]$ using the public key Pub_{RA_k} of the associated RA_k to extract $RegCred_{SD_i} = \{RID_{SD_i},\ TC_{SD_i},\ Pub_{SD_i},\ E_q(\alpha, \beta),\ G_k\}$. On successful matching of the decrypted RID_{GN_j} with its received version, GN_j checks the validity of the signature $ECDSA.Sign_{mk_{RA_k}}[RegCred_{GN_j}]$ using the public key Pub_{RA_k}. Upon successful signature validation, GN_j stores $RegCred_{GN_j}$ in its secure database for the mutual authentication and key establishment purpose.

We now discuss the following steps needed for the access control between SD_i and GN_j with the help of the obtained registration credentials $RegCred_{SD_i}$ and $RegCred_{GN_j}$ from the BC, respectively.

- *Step AC1.* SD_i picks a random secret $rs_{SD_i} \in Z_q^*$ and the current timestamp TS_{SD_i} for computing
  $RS_{SD_i} = h(TC_{SD_i} || rs_{SD_i} || pr_{SD_i} || RID_{SD_i} || TS_{SD_i}) \cdot G_k$.
  Furthermore, SD_i computes signature on rs_{SD_i} as
  $Sig_{SD_i} = h(TC_{SD_i} || rs_{SD_i} || pr_{SD_i} || RID_{SD_i} || TS_{SD_i})$ $+ h(RID_{SD_i} || Pub_{SD_i} || Pub_{GN_j} || TS_{SD_i}) * pr_{SD_i} \pmod q$.
  SD_i then sends access control request message $Msg_{AC1} = \{RID_{SD_i},\ Sig_{SD_i},\ RS_{SD_i},\ TS_{SD_i}\}$ to its corresponding gateway node GN_j via open channel.
- *Step AC2.* If the message Msg_{AC1} is received at time $TS_{SD_i}^*$, the GN_j first checks timeliness of received TS_{SD_i} by verifying $|TS_{SD_i}^* - TS_{SD_i}| < \Delta T$, where ΔT signifies the "maximum transmission delay with a message". If it is valid, GN_j retrieves Pub_{SD_i} corresponding to RID_{SD_i} from its own database and verifies the received signature Sig_{SD_i} by the condition:
  $Sig_{SD_i} \cdot G_k = RS_{SD_i} + h(RID_{SD_i} || Pub_{SD_i} || Pub_{GN_j}$ $|| TS_{SD_i}) \cdot Pub_{SD_i}$.
  Upon successful signature validation, GN_j validates SD_i as authentic device, creates a random secret $rs_{GN_j} \in Z_q^*$ and the current timestamp TS_{GN_j} for calculating
  $RS_{GN_j} = h(TC_{GN_j} || rs_{GN_j} || pr_{GN_j} || RID_{GN_j} || TS_{GN_j}) \cdot G_k$
  and the Diffie-Hellman type key
  $DHK_{GN_j,SD_i} = h(TC_{GN_j} || rs_{GN_j} || pr_{GN_j} || RID_{GN_j}$ $|| TS_{GN_j}) \cdot RS_{SD_i}$.
  Furthermore, GN_j evaluates its own polynomial share $g_j(RID_{GN_j}, y)$ at the point $y = RID_{SD_i}$ to obtain
  $g_j(RID_{GN_j}, RID_{SD_i})$,
  $y_{GN_j} = h(g_j(RID_{GN_j}, RID_{SD_i}) || Sig_{SD_i} || TS_{GN_j})$ $\oplus h(DHK_{GN_j,SD_i} || TS_{SD_i} || TS_{GN_j})$,

and also computes the signature on rs_{GN_j} and DHK_{GN_j,SD_i} as
$Sig_{GN_j} = h(TC_{GN_j} || rs_{GN_j} || pr_{GN_j} || RID_{GN_j} || TS_{GN_j}) + h(RID_{GN_j} || RID_{SD_i} || Pub_{GN_j} || DHK_{GN_j,SD_i} || y_{GN_j}) * pr_{GN_j} \pmod q$.
Next, GN_j dispatches the access control response message $Msg_{AC2} = \{RID_{GN_j}, Sig_{GN_j}, RS_{GN_j}, y_{GN_j}, TS_{GN_j}\}$ to its corresponding SD_i via open channel.

- *Step AC3.* Let SD_i receive the message Msg_{AC2} at time $TS^*_{GN_j}$. SD_i then checks TS_{GN_j}'s validity by $|TS^*_{GN_j} - TS_{GN_j}| < \Delta T$ and if it is valid, SD_i fetches Pub_{GN_j} corresponding to RID_{GN_j} from its memory. SD_i calculates the Diffie-Hellman type key
$DHK_{SD_i,GN_j} = h(TC_{SD_i} || rs_{SD_i} || pr_{SD_i} || RID_{SD_i} || TS_{SD_i}) \cdot RS_{GN_j}$,
$z_{SD_i} = y_{GN_j} \oplus h(DHK_{SD_i,GN_j} || TS_{SD_i} || TS_{GN_j})$,
which should be equal to $h(g_j(RID_{GN_j}, RID_{SD_i}) || Sig_{SD_i} || TS_{GN_j})$, and verifies the signature by the condition:
$Sig_{GN_j} \cdot G_k = RS_{GN_j} + h(RID_{GN_j} || RID_{SD_i} || Pub_{GN_j} || DHK_{SD_i,GN_j} || y_{GN_j}) \cdot Pub_{GN_j}$.
Upon successful signature validation, SD_i authenticates GN_j as valid, generates current timestamp TS'_{SD_i}, and computes the session key shared with GN_j as $SK_{SD_i,GN_j} = h(DHK_{SD_i,GN_j} || z_{SD_i})$ and its verifier
$SKV_{SD_i,GN_j} = h(SK_{SD_i,GN_j} || TS'_{SD_i})$.
Finally, SD_i sends the acknowledgment message $Msg_{AC3} = \{SKV_{SD_i,GN_j}, TS'_{SD_i}\}$ to GN_j via public channel.
- *Step AC4.* Upon reception of the message Msg_{AC3} at time $TS^{**}_{SD_i}$, GN_j checks timeliness of received TS'_{SD_i} by verifying $|TS^{**}_{SD_i} - TS'_{SD_i}| < \Delta T$. If the validation passes, GN_j then calculates the session key shared with SD_i as
$SK_{GN_j,SD_i} = h(DHK_{GN_j,SD_i} || h(g_j(RID_{GN_j}, RID_{SD_i}) || Sig_{SD_i} || TS_{GN_j}))$
and its verifier
$SKV_{GN_j,SD_i} = h(SK_{GN_j,SD_i} || TS'_{SD_i})$.
If the verification condition:
$SKV_{GN_j,SD_i} = SKV_{SD_i,GN_j}$
holds good, both GN_j and SD_i store the same session key $SK_{GN_j,SD_i} (= SK_{SD_i,GN_j})$ for their secret communications.

C. KEY MANAGEMENT PHASE

Before the key management process starts, an edge server (ES_l) needs to obtain its registration credentials from the BS like SD_i and GN_j as discussed in Section III-B. Note that GN_j already obtained its registration credentials from the BC and stored in its secure database. ES_l issues a request $RegCredReq_{ES_l} = \{RID_{ES_l}\}$ for obtaining its registration credentials to the BC over open channel. Once the BC checks the validity of RID_{ES_l}, it fetches the corresponding transaction $Tx_{RegCred_{ES_l}} = \langle RID_{ES_l}, E_{Pub_{ES_l}}[RegCred_{ES_l}], ECDSA.Sign_{mk_{RA_k}}[RegCred_{ES_l}]\rangle$ and sends it to ES_l over public channel. After decrypting $E_{Pub_{ES_l}}[RegCred_{ES_l}]$ using the private key pr_{ES_l}, ES_l extracts $RegCred_{ES_l} = \{RID_{ES_l}, g_j(RID_{ES_l}, y), TC_{ES_l}, Pub_{ES_l}, E_q(\alpha, \beta), G_k\}$ and checks the validity of both the decrypted RID_{ES_l} and the signature $ECDSA.Sign_{mk_{RA_k}}[RegCred_{ES_l}]$. If all these are valid, ES_l stores $RegCred_{ES_l}$ in its secure database which is used for the key management purpose as discussed below.

The sole goal of this phase is to setup a (pairwise) secret key between a gateway node (GN_j) and its corresponding edge server (ES_l) for their communications. This phase involves the exchange of three messages, namely Msg_{KM1}, Msg_{KM2} and Msg_{KM3} between GN_j and ES_l, that use the registration credentials obtained from the BC along with random generated secrets and current timestamps. After verifying the message Msg_{KM1}, ES_l generates the session key shared with GN_j and sends the message Msg_{KM2} to GN_j. Validation of Msg_{KM2} by GN_j assures mutual authentication between GN_j and ES_l. Furthermore, verification of Msg_{KM3} guarantees that the "session key established between GN_j and ES_l are same and legitimate".

We now explain the followings stages:

- *Step KM1.* The initiator GN_j first creates a random secret $rs_{GN_{j1}} \in Z^*_q$ and a current timestamp $TS_{GN_{j1}}$ in order to calculate
$RS_{GNj1} = h(RID_{GN_j} || rs_{GN_{j1}} || TC_{GN_j} || TS_{GN_{j1}} || pr_{GN_j}) \cdot G_k$.
Next, GN_j calculates the signature on $rs_{GN_{j1}}$ as
$Sig_{GN_{j1}} = h(RID_{GN_j} || rs_{GN_{j1}} || TC_{GN_j} || TS_{GN_{j1}} || pr_{GN_j}) + h(RID_{GN_j} || Pub_{GN_j} || Pub_{ES_l} || TS_{GN_{j1}}) * pr_{GN_j} \pmod q$
and dispatches the request message $Msg_{KM1} = \{RID_{GN_j}, RS_{GN_{j1}}, Sig_{GN_{j1}}, TS_{GN_{j1}}\}$ to its respective ES_l via open channel.
- *Step KM2.* After receiving Msg_{KM1}, if the timeliness check of the received timestamp $TS_{GN_{j1}}$ passes, ES_l proceeds to verify signature $Sig_{GN_{j1}}$ by the condition:
$Sig_{GN_{j1}} \cdot G_k = RS_{GN_{j1}} + h(RID_{GN_j} || Pub_{GN_j} || Pub_{ES_l} || TS_{GN_{j1}}) \cdot Pub_{GN_j}$.
Now, if the signature is valid, ES_l treats GN_j as valid, and creates a random secret $rs_{ES_{l2}} \in Z^*_q$ and current timestamp $TS_{ES_{l2}}$ to calculate
$RS_{ES_{l2}} = h(RID_{ES_l} || pr_{ES_l} || rs_{ES_{l2}} || TS_{ES_{l2}}) \cdot G_k$
and the Diffie-Hellman type key
$DHK_{ES_l,GN_j} = h(RID_{ES_l} || pr_{ES_l} || rs_{ES_{l2}} || TS_{ES_{l2}}) \cdot RS_{GN_{j1}}$.
After these computations, ES_l also evaluates its own polynomial share $g_j(RID_{ES_l}, y)$ at the point $y = RID_{GN_j}$ to have the secret $g_j(RID_{ES_l}, RID_{GN_j})$, and then computes the secret pairwise key shared with GN_j as $SK_{ES_l,GN_j} = h(DHK_{ES_l,GN_j} || g_j(RID_{ES_l}, RID_{GN_j}))$ and a signature on both $rs_{ES_{l2}}$ and SK_{ES_l,GN_j} as
$Sig_{ES_{l2}} = h(RID_{ES_l} || pr_{ES_l} || rs_{ES_{l2}} || TS_{ES_{l2}}) + h(Pub_{ES_l} || SK_{ES_l,GN_j} || TS_{ES_{l2}}) * pr_{ES_l} \pmod q$.
Next, ES_l dispatches the response message $Msg_{KM2} = \{RID_{ES_l}, RS_{ES_{l2}}, Sig_{ES_{l2}}, TS_{ES_{l2}}\}$ to GN_j via open channel.
- *Step KM3.* After checking the timeliness of the timestamp $TS_{ES_{l2}}$ in the received message Msg_{KM2}, GN_j computes the "Diffie-Hellman type key"

Access Control Phase	
IoT smart device (SD_i)	Gateway node (GN_j)
Obtain registration credentials from the blockchain center (BC).	Obtain registration credentials from the blockchain center (BC).
Generates random secret $rs_{SD_i} \in Z_q^*$, current timestamp TS_{SD_i}. Calculate $RS_{SD_i} = h(TC_{SD_i} \|\| rs_{SD_i} \|\| pr_{SD_i} \|\| RID_{SD_i} \|\| TS_{SD_i}) \cdot G_k$, $Sig_{SD_i} = h(TC_{SD_i} \|\| rs_{SD_i} \|\| pr_{SD_i} \|\| RID_{SD_i} \|\| TS_{SD_i}) + h(RID_{SD_i} \|\| Pub_{SD_i} \|\| Pub_{GN_j} \|\| TS_{SD_i}) * pr_{SD_i} \pmod{q}$. $\xrightarrow{Msg_{AC1} = \{RID_{SD_i}, Sig_{SD_i}, RS_{SD_i}, TS_{SD_i}\}}$ (via open channel)	Check if $\|TS^*_{SD_i} - TS_{SD_i}\| < \Delta T$? If valid, retrieve Pub_{SD_i} corresponding to RID_{SD_i}. Verify signature Sig_{SD_i}. If valid, generate random secret $rs_{GN_j} \in Z_q^*$, current timestamp TS_{GN_j}. Calculate $RS_{GN_j} = h(TC_{GN_j} \|\| rs_{GN_j} \|\| pr_{GN_j} \|\| RID_{GN_j} \|\| TS_{GN_j}) \cdot G_k$, $DHK_{GN_j,SD_i} = h(TC_{GN_j} \|\| rs_{GN_j} \|\| pr_{GN_j} \|\| RID_{GN_j} \|\| TS_{GN_j}) \cdot RS_{SD_i}$, $g_j(RID_{GN_j}, RID_{SD_i})$, $y_{GN_j} = h(g_j(RID_{GN_j}, RID_{SD_i}) \|\| Sig_{SD_i} \|\| TS_{GN_j}) \oplus h(DHK_{GN_j,SD_i} \|\| TS_{SD_i} \|\| TS_{GN_j})$, $Sig_{GN_j} = h(TC_{GN_j} \|\| rs_{GN_j} \|\| pr_{GN_j} \|\| RID_{GN_j} \|\| TS_{GN_j}) + h(RID_{GN_j} \|\| RID_{SD_i} \|\| Pub_{GN_j} \|\| DHK_{GN_j,SD_i} \|\| y_{GN_j}) * pr_{GN_j} \pmod{q}$. $\xleftarrow{Msg_{AC2} = \{RID_{GN_j}, Sig_{GN_j}, RS_{GN_j}, y_{GN_j}, TS_{GN_j}\}}$ (via open channel)
Check if $\|TS^*_{GN_j} - TS_{GN_j}\| < \Delta T$? If valid, retrieve Pub_{GN_j} corresponding to RID_{GN_j}. Calculate $DHK_{SD_i,GN_j} = h(TC_{SD_i} \|\| rs_{SD_i} \|\| pr_{SD_i} \|\| RID_{SD_i} \|\| TS_{SD_i}) \cdot RS_{GN_j}$, $z_{SD_i} = y_{GN_j} \oplus h(DHK_{SD_i,GN_j} \|\| TS_{SD_i} \|\| TS_{GN_j})$. $Sig_{GN_j} \cdot G_k = RS_{GN_j} + h(RID_{GN_j} \|\| RID_{SD_i} \|\| Pub_{GN_j} \|\| DHK_{SD_i,GN_j} \|\| y_{GN_j}) \cdot Pub_{GN_j}$? If valid, generate current timestamp TS'_{SD_i}. Compute $SK_{SD_i,GN_j} = h(DHK_{SD_i,GN_j} \|\| z_{SD_i})$, $SKV_{SD_i,GN_j} = h(SK_{SD_i,GN_j} \|\| TS'_{SD_i})$. $\xrightarrow{Msg_{AC3} = \{SKV_{SD_i,GN_j}, TS'_{SD_i}\}}$ (via open channel)	Checks if $\|TS^{**}_{SD_i} - TS'_{SD_i}\| < \Delta T$? If valid, calculate $SK_{GN_j,SD_i} = h(DHK_{GN_j,SD_i} \|\| h(g_j(RID_{GN_j}, RID_{SD_i}) \|\| Sig_{SD_i} \|\| TS_{GN_j}))$, $SKV_{GN_j,SD_i} = h(SK_{GN_j,SD_i} \|\| TS'_{SD_i})$. Verify if $SKV_{GN_j,SD_i} = SKV_{SD_i,GN_j}$? If valid, session key is valid and $SK_{GN_j,SD_i} (= SK_{SD_i,GN_j})$.

Key Management Phase	
Gateway node (GN_j)	Edge server (ES_l)
	Obtain registration credentials from the blockchain center (BC).
Create random secret $rs_{GN_{j1}} \in Z_q^*$, current timestamp $TS_{GN_{j1}}$. Calculate $RS_{GNj1} = h(RID_{GN_j} \|\| rs_{GN_{j1}} \|\| TC_{GN_j} \|\| TS_{GN_{j1}} \|\| pr_{GN_j}) \cdot G_k$, $Sig_{GN_{j1}} = h(RID_{GN_j} \|\| rs_{GN_{j1}} \|\| TC_{GN_j} \|\| TS_{GN_{j1}} \|\| pr_{GN_j}) + h(RID_{GN_j} \|\| Pub_{GN_j} \|\| Pub_{ES_l} \|\| TS_{GN_{j1}}) * pr_{GN_j} \pmod{q}$. $\xrightarrow{Msg_{KM1} = \{RID_{GN_j}, RS_{GN_{j1}}, Sig_{GN_{j1}}, TS_{GN_{j1}}\}}$ (via open channel)	Check validity of timestamp $TS_{GN_{j1}}$. If valid, further verify signature $Sig_{GN_{j1}}$. If valid, create random $rs_{ES_{l2}} \in Z_q^*$, current timestamp $TS_{ES_{l2}}$. Calculate $RS_{ES_{l2}} = h(RID_{ES_l} \|\| pr_{ES_l} \|\| rs_{ES_{l2}} \|\| TS_{ES_{l2}}) \cdot G_k$, $DHK_{ES_l,GN_j} = h(RID_{ES_l} \|\| pr_{ES_l} \|\| rs_{ES_{l2}} \|\| TS_{ES_{l2}}) \cdot RS_{GN_{j1}}$. Obtain $g_j(RID_{ES_l}, RID_{GN_j})$, and compute $SK_{ES_l,GN_j} = h(DHK_{ES_l,GN_j} \|\| g_j(RID_{ES_l}, RID_{GN_j}))$, and signature $Sig_{ES_{l2}} = h(RID_{ES_l} \|\| pr_{ES_l} \|\| rs_{ES_{l2}} \|\| TS_{ES_{l2}}) + h(Pub_{ES_l} \|\| SK_{ES_l,GN_j} \|\| TS_{ES_{l2}}) * pr_{ES_l} \pmod{q}$. $\xleftarrow{Msg_{KM2} = \{RID_{ES_l}, RS_{ES_{l2}}, Sig_{ES_{l2}}, TS_{ES_{l2}}\}}$ (via open channel)
Check validity of $TS_{ES_{l2}}$. If valid, compute $DHK_{GN_j,ES_l} = h(RID_{GN_j} \|\| rs_{GN_{j1}} \|\| TC_{GN_j} \|\| TS_{GN_{j1}} \|\| pr_{GN_j}) \cdot RS_{ES_{l2}}$ $SK_{GN_j,ES_l} = h(DHK_{GN_j,ES_l} \|\| g_j(RID_{GN_j}, RID_{ES_l}))$. Verify signature $Sig_{ES_{l2}}$. If signature is valid, established key is legitimate, and $SK_{GN_j,ES_l} (= SK_{ES_l,GN_j})$.	

FIGURE 3. Summary of access control and key management phases.

$DHK_{GN_j,ES_l} = h(RID_{GN_j} \,||rs_{GN_{j1}} \,||TC_{GN_j} \,||TS_{GN_{j1}} \,||pr_{GN_j}) \cdot RS_{ES_{l2}}$,
$g_j(RID_{GN_j}, RID_{ES_l}) = g_j(RID_{ES_l}, RID_{GN_j})$
using its own polynomial share $g_j(RID_{GN_j}, y)$ as $g_j(x, y) = g_j(y, x)$ and the session key shared with ES_l as $SK_{GN_j,ES_l} = h(DHK_{GN_j,ES_l}||g_j(RID_{GN_j}, RID_{ES_l}))$. Next, GN_j verifies the signature $Sig_{ES_{l2}}$ as
$Sig_{ES_{l2}} \cdot G_k = RS_{ES_{l2}} + h(Pub_{ES_l} \,||SK_{GN_j,ES_l} \,||TS_{ES_{l2}}) \cdot Pub_{ES_l}$.
If the signature validation passes, GN_j also treats ES_l as authentic entity.

Finally, both GN_j and ES_l require to store the same secret pairwise key SK_{GN_j,ES_l} $(= SK_{ES_l,GN_j})$ for their secure communications. Both the access control and key management phases are explained briefly in Figure 3.

Block Header	
Block Version	$BlkV$
Previous Block Hash	$PreBH$
Merkle Tree Root	$MrkTR$
Industry Type	$IT_m, m = 1, 2, \cdots, w$ (Type of an IIoT applications)
Timestamp	TS_{ES_l}
Creator of Block	$CreB_{ID}$ (Identity of an ES_l in P2P network)
Public Key of Signer ES_l	Pub_{ES_l}
Block Payload (Encrypted Transactions)	
List of t_n Encrypted Transactions $\#i$ (Tx_i)	$\{E_{Pub_{ES_l}}(Tx_i) \mid i = 1, 2, \cdots, t_n\}$
Current Block Hash	$CurBH$
Signature on $CurBH$	$Sig_{Block_k} = ECDSA.Sig_{pr_{ES_l}}(CurBH)$

FIGURE 4. Architecture of a block $Block_k$ for various transactions.

D. BLOCK CREATION, VERIFICATION, AND ADDITION IN BLOCKCHAIN

In this section, we elaborate the process of block creation, verification and addition of that block in the blockchain. For this issue, the IoT smart devices first send the messages encrypted with their established session keys as described during the "access control phase" in Section III-B to their respective gateway node(s). In turn, the gateway nodes also send the information encrypted with their secret keys established during the"key management phase" in Section III-C to their respective edge servers. An edge server ES_l is then responsible to construct a block containing the encrypted transactions of information received from the gateway node(s) or IoT smart device(s) for a particular application. Here, the ECC public key Pub_{ES_l} is used for generating the encrypted transactions because the information is strictly private and confidential with respect to an IIoT application. ES_l creates Merkle tree root on the encrypted transactions along with timestamp and random number. The current hash block is computed as $CurBH = h(BlkV \,||PreBH \,||MrkTR \,||IdtT_m \,||TS_{ES_l} \,||CreB_{ID} \,||Pub_{ES_l} \,||\{E_{Pub_{ES_l}}(Tx_i) \,|i = 1, 2, \cdots, t_n\})$ and the signature on $CurBH$ as $Sig_{Block_k} = ECDSA.Sig_{pr_{ES_l}}(CurBH)$ where $ECDSA.Sig(\cdot)$ denotes the "ECDSA signature generation algorithm". The overall structure of a block $Block_k$ is shown in Figure 4. The encryption is used in the transactions to make the transactions private with the edge server so that other P2P servers can not decrypt without private key of the particular edge server. Since the encryption is performed with the help of Pub_{ESl}, so only particular edge server associated with an application can see and decrypt the data. Finally, through the consensus algorithm provided in Figure 5, a leader among the group edge servers in the P2P network is selected using the existing leader selection algorithm [58] and then the leader sends the created block, say $Block_k$ to its peer nodes to have the consensus among them for verifying and adding the block in their local ledgers of blockchain center containing the fog servers. Note that we have applied the "Practical Byzantine Fault Tolerance (PBFT)" algorithm [8] for consensus purpose. However, we have provided the voting-based PBFT version as the proposed consensus algorithm, in which a leader L selected among the P2P network, generates a current timestamp TS_L and a random number r_L to perform voting process. L then creates signature Sig_L using the ECDSA signature generation algorithm with its own private key pr_L on the message $h(Block_k \,||TS_L \,||r_L \,||VTR_{req})$, where VTR_{req} is voting request, and sends the request message $\langle Block_k, Sig_L, E_{Pub_{ES_l}}[r_L, VTR_{req}], TS_L\rangle$ to each other edge server ES_l via public channel. After successful validation of timestamp TS_L, Merkle tree root $MrkTR$, current block hash $CurBH$ and signature on block Sig_{Block_k}, each other node in the P2P network sends the response message $\langle E_{Pub_L}[r_L, TS_{ES_l}, VTR_{res}], TS_{ES_l}\rangle$ to L via public channel, where VTR_{res} is the "voting response" and TS_{ES_l} is the "current timestamp".

An edge server associated with an IIoT application is responsible to create the blocks and store them into the blockchain after the consensus process as described in Figure 5.

Remark 3: In this work, we have mainly considered the private blockchain scenario where the data is private and confidential with respect to each edge server. However, there are some applications, where the data needs to be shared inside the system. Thus, encrypting them will make the entities without the secret keys unable to decrypt the data and use the data. In this case, the edge servers can maintain a group (secret) key among them so that the selected shared data (transactions) can be now encrypted with the help of the group key using symmetric key encryption. Hence, the shared encrypted data can be decrypted by other edge servers using the same group key.

E. DYNAMIC IoT SMART DEVICE ADDITION PHASE

Due to hostile environment/power exhaustion of IoT smart devices, the devices may be either physically captured or shut down. To continue the functionality of IIoT environment, new smart device, say SD^{new} needs to be added. Prior to deployment, SD^{new} is required to register by the trusted registration authority RA_k in that particular application where existing other smart devices are already there. For registering

SD^{new}, RA_k needs to follow the same steps as described in the IoT smart devices registration (see Section III-A1).

IV. SECURITY ANALYSIS

In this section, we discourse the security analysis to show that the proposed PBACS-PECIIoT is resilient against the following potential attacks.

A. FORMAL SECURITY ANALYSIS UNDER ROR MODEL

In this section, we discuss about the "session key security under broadly-recognized Real-Or-Random (ROR) oracle model [59] to show that PBACS-PECIIoT is secure against an adversary $\mathcal{A}$ for deriving the session-key between a smart device (SD_i) and a gateway node (GN_j) during the access control phase" described in Section III-B. It is worth noticing that the "ROR-model based security analysis" provides the semi-formal security proof where the advantage of an adversary, say $\mathcal{A}$, is computed, and $\mathcal{A}$ attempts to derive the session key among two communicating entities in the network.

Algorithm 1 Voting-based consensus for verification and addition of a block $(Block_k)$

Input: $Block_k$ = {Block Header, Block Payload, $CurBH$, Sig_{Block_k}}; private-public key pairs (pr_{ES_l}, Pub_{ES_l}), and $n_{f_{ES_l}}$ represents the number of faulty nodes in P2P network.

Output: Commitment & addition of $Block_k$ in the blockchain after successful validation.

```
1: Assume a leader has been selected by $ES_l$, say $L$ using the leader selection algorithm [41].
2: $L$ generates current timestamp $TS_L$ and a random number $r_L$ to perform voting process. $L$ creates signature $Sig_L$ using ECDSA signature generation algorithm with its own private key $pr_L$ on the message $h(Block_k || TS_L || r_L || VTR_{req})$, where $VTR_{req}$ is voting request.
3: $L$ sends the request message $\langle Block_k, Sig_L, E_{Pub_{ES_l}}[r_L, VTR_{req}], TS_L\rangle$ to each other edge server $ES_l$ via public channel.
4: After receiving request message, each $ES_l$ checks timestamp $TS_L$ and if it is valid, it computes $(r_L, VTR_{req}) = D_{pr_{ES_l}}[E_{Pub_{ES_l}}[r_L, VTR_{req}]]$, verifies $Sig_L$ using ECDSA signature verification algorithm [39].
5: If the signature is valid, $ES_l$ further verifies $MrkTR$, $CurBH$, and $Sig_{Block_k}$ on received block $Block_k$.
6: After all the successful validations, $ES_l$ sends the response message $\langle E_{Pub_L}[r_L, TS_{ES_l}, VTR_{res}], TS_{ES_l}\rangle$ to $L$ via public channel, where $VTR_{res}$ is the voting response and $TS_{ES_l}$ is current timestamp.
7: Assume that $VCount$ represents the number of valid votes. Set $VCount \leftarrow 0$.
8: for each received message $\langle E_{Pub_L}[r_L, TS_{ES_l}, VTR_{res}], TS_{ES_l}\rangle$ from other edge nodes $ES_l$ do
9:     $L$ first checks validity of timestamp $TS_{ES_l}$, decrypts message using its private key $pr_L$ and validates $r_L$, $TS_{ES_l}$ and $VTR_{esp}$. If all are valid, set $VCount = VCount + 1$.
10: end for
11: if $(VCount > 2n_{f_{ES_l}} + 1)$ then
12:     $L$ sends commit response for successful verification of $Block_k$ to its all followers $ES_l$.
13:     Each $ES_l$ and $L$ then add $Block_k$ to their local ledgers.
14: end if
```

FIGURE 5. Voting-based consensus for verification and addition of a block (*Block*$_k$).

1) RANDOM ORACLE MODEL

We first describe the respective security model that is based on the works by Bellare et al. [60] and Wu et al. [53], for the proposed scheme, that goes through a sequence of the interactive games between a challenger and an adversary. Here, the main intention is to prove that the proposed scheme provides the session key security against the adversary.

The adversary $\mathcal{A}$ is permitted to execute the following queries for deriving the session key:

- *Execute*$(\Theta^{a_1}_{SD_i}, \Theta^{a_2}_{GN_j})$: $\mathcal{A}$ carries out this query to eavesdrop the messages exchanged between SD_i and GN_j.
- *CorruptSD*$(\Theta^{a_1}_{SD_i})$: It allows $\mathcal{A}$ to extract "the credentials stored in a stolen or lost SD_i's memory".
- *Reveal*(Θ^a): By executing this query, the session key SK_{SD_i,GN_j} $(= SK_{GN_j,SD_i})$ is exposed to $\mathcal{A}$ that is shared between Θ^a and its respective associate.
- *Test*(Θ^a): $\mathcal{A}$ is allowed to perform Θ^a to verify if the session key SK_{SD_i,GN_j} $(= SK_{GN_j,SD_i})$ is real or a random key.

Definition 1 of the semantic security is used to show the session key security of PBACS-PECIIoT in Theorem 1. In addition, as discussed in [61], a "collision-resistant one-way cryptographic hash function $h(\cdot)$ is accessed to all the involved participants including the adversary $\mathcal{A}$". As a result, we also model "$h(\cdot)$ as a random oracle, say *hash*". The ROR model is associated with the following components:

Participants. As we consider the access control between smart device SD_i and gateway node GN_j mentioned in Section III-B, two participants, namely SD_i and GN_j are engaged for communication, and apart from these entities the registration authority RA_k is also involved during offline registration purpose and dynamic node addition phase. The notations $\Theta^{a_1}_{SD_i}$ and $\Theta^{a_2}_{GN_j}$ signify the a_1^{th} and a_2^{th} instances of SD_i and GN_j, respectively. These instances are known as the "random oracles".

Accepted state. An instance Θ^a will enter in its "accepted state" once it goes to an accept state when the last valid protocol message is received. If all the communicated messages (sent and received) are put in an ordered sequence, it creates a "session identification *sid* of Θ^a for the current session".

Partnering. Two instances (Θ^{a_1} and Θ^{a_2}) will be the partners to each other if the following are fulfilled: a) Θ^{a_1} and Θ^{a_2} are in "accepted states"; b) Θ^{a_1} and Θ^{a_2} share the same *sid* and also "mutually authenticate each other"; and c) Θ^{a_1} and Θ^{a_2} are "mutual partners of each other".

Freshness. An instance $\Theta^{a_1}_{SD_i}$ or $\Theta^{a_2}_{GN_j}$ is *fresh* if the established session key SK_{SD_i,GN_j} $(= SK_{GN_j,SD_i})$ shared between SD_i and GN_j is not revealed to $\mathcal{A}$ using the Reveal(Θ^a) query described above.

We now define the "semantic security" in Definition 1 prior to prove Theorem 1.

Definition 1 (Semantic security): The "advantage of an adversary $\mathcal{A}$ running in polynomial time t in breaking *the semantic security of the proposed PBACS-PECIIoT for deriving the session key SK_{SD_i,GN_j} $(= SK_{GN_j,SD_i})$ among a smart device SD_i and a gateway node GN_j" in a particular session during the access control phase (ACP) is $Adv^{PBACS-PECIIoT}_{\mathcal{A},ACP}(t) = |2Pr[c' = c] - 1|$, where "c and c′ are respectively the correct and guessed bits".*

2) PROVABLE SECURITY

In this section, we apply the random oracle model discussed above in order to prove that the proposed scheme provides the session key security that is described in Theorem 1.

Theorem 1: The advantage $Adv^{PBACS-PECIIoT}_{\mathcal{A},ACP}(t)$ of an adversary $\mathcal{A}$ running in polynomial time t in order to derive the session key SK_{SD_i,GN_j} $(= SK_{GN_j,SD_i})$ established between SD_i and GN_j in a particular session during the access control phase (ACP) for the proposed PBACS-PECIIoT is $Adv^{PBACS-PECIIoT}_{\mathcal{A},ACP}(t) \leq \frac{q_h^2}{|hash|} + 2Adv^{ECDDHP}_{\mathcal{A}}(t)$, where q_h, $|hash|$, and $Adv^{ECDDHP}_{\mathcal{A}}(t)$ represent the "number of *hash* queries", the "range space of a one-way collision-resistant hash function $h(\cdot)$", and the "advantage of breaking the Elliptic Curve Decisional Diffie-Hellman Problem (ECDDHP)", respectively.

Proof: A similar proof is followed here as in [61]. In the proposed PBACS-PECIIoT, we consider three games, namely $Game_i^{\mathcal{A}}$ for the adversary $\mathcal{A}$, $i = 0, 1, 2$. We define $Succ^{\mathcal{A}}_{Game_i}$ as an event wherein $\mathcal{A}$ can guess the random bit c correctly in the game $Game_i^{\mathcal{A}}$. Therefore, $\mathcal{A}$'s advantage to win the $Game_i^{\mathcal{A}}$ in the proposed PBACS-PECIIoT becomes $Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_i} = Pr[Succ^{\mathcal{A}}_{Game_i}]$. The games are now defined as follows.

$\mathbf{Game_0^{\mathcal{A}}}$: Under this game, the adversary $\mathcal{A}$ plays a real attack under the ROR model for the initial game $Game_0^{\mathcal{A}}$. Prior to beginning of the game $Game_0^{\mathcal{A}}$, $\mathcal{A}$ needs to pick a random bit c. Therefore, the advantage of $Game_0^{\mathcal{A}}$ is then

$$Adv^{PBACS-PECIIoT}_{\mathcal{A},ACP}(t) = |2Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_0} - 1|. \quad (1)$$

$\mathbf{Game_1^{\mathcal{A}}}$: In this game, $\mathcal{A}$ applies the eavesdropping attack to derive the session key for a particular session. $\mathcal{A}$ performs the *Execute* query to intercept all the communicated messages $Msg_{AC1} = \{RID_{SD_i}, Sig_{SD_i}, RS_{SD_i}, TS_{SD_i}\}$, $Msg_{AC2} = \{RID_{GN_j}, Sig_{GN_j}, RS_{GN_j}, y_{GN_j}, TS_{GN_j}\}$ and $Msg_{AC3} = \{SKV_{SD_i,GN_j}, TS'_{SD_i}\}$ during the access control phase (ACP) between SD_i and GN_j mentioned in SectionIII-B. After that, $\mathcal{A}$ may try to generate the session key $SK_{SD_i,GN_j} = h(DHK_{SD_i,GN_j} \,||z_{SD_i})$, where $DHK_{SD_i,GN_j} = h(TC_{SD_i} \,||rs_{SD_i} \,||pr_{SD_i} \,||RID_{SD_i} \,||TS_{SD_i}) \cdot RS_{GN_j}$ and $z_{SD_i} = y_{GN_j} \oplus h(DHK_{SD_i,GN_j} \,||TS_{SD_i} \,||TS_{GN_j})$. Without knowledge of the long term secrets $\{TC_{SD_i}, pr_{SD_i}\}$ and $\{TC_{GN_j}, pr_{GN_j}\}$, $\mathcal{A}$ cannot succeed to derive the session key SK_{SD_i,GN_j} $(= SK_{GN_j,SD_i})$. As the credentials are protected by the "cryptographic hash function $h(\cdot)$", $\mathcal{A}$ will be unable to derive the session key even by executing the *Reveal* and *Test* queries. Therefore, the games $\mathbf{Game_1^{\mathcal{A}}}$ and $\mathbf{Game_0^{\mathcal{A}}}$ are both indistinguishable under such an eavesdropping attack. The following outcome is then produced:

$$Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_1} = Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_0}. \quad (2)$$

$\mathbf{Game_2^{\mathcal{A}}}$: In this game, the adversary $\mathcal{A}$ plays an active attack. $\mathcal{A}$ simulates the *hash* and *CorruptSD* queries and tries to solve computational ECDDHP problem. $\mathcal{A}$ needs to obtain $DHK_{SD_i,GN_j} = h(TC_{SD_i} \,||rs_{SD_i} \,||pr_{SD_i} \,||RID_{SD_i} \,||TS_{SD_i}) \cdot RS_{GN_j}$ $(= DHK_{GN_j,SD_i})$ to derive the session key SK_{SD_i,GN_j}. Assume that $\mathcal{A}$ hijacks all the transmitted message $\{Msg_{AC1}, Msg_{AC2}, Msg_{AC3}\}$. Thus, $\mathcal{A}$ knows the values RS_{SD_i} and RS_{GN_j}. From RS_{SD_i} and RS_{GN_j}, $\mathcal{A}$ may try to compute the secret values $h(TC_{SD_i} \,||rs_{SD_i} \,||pr_{SD_i} \,||RID_{SD_i} \,||TS_{SD_i})$ and $h(TC_{GN_j} \,||rs_{GN_j} \,||pr_{GN_j} \,||RID_{GN_j} \,||TS_{GN_j})$, respectively. However, to derive these secrets credentials, $\mathcal{A}$ needs to know the long term secrets $\{TC_{SD_i}, pr_{SD_i}, TC_{GN_j}, pr_{GN_j}\}$, which becomes difficult problem due to solving ECDDHP. Moreover, the secrets are enclosed by a "one-way collision-resistant hash function $(h(\cdot))$". In addition, $\mathcal{A}$ will execute *CorruptSD* to extract all the secret credentials $\{RID_{SD_i}, TC_{SD_i}, (pr_{SD_i}, Pub_{SD_i}), h(\cdot), E_q(\alpha, \beta), G_k\}$, but he/she has no knowledge about the random secrets (short term secrets)$\{rs_{SD_i}, rs_{GN_j}\}$. If $\mathcal{A}$ is aware of the long term secrets as well as short term, then only he/she gets the session key SK_{SD_i,GN_j} $(= SK_{GN_j,SD_i})$. Therefore, the games $\mathbf{Game_2^{\mathcal{A}}}$ and $\mathbf{Game_1^{\mathcal{A}}}$ are indistinguishable if we exclude the *hash* and *CorruptSD* queries in $\mathbf{Game_2^{\mathcal{A}}}$. The birthday paradox result on "one-way collision-resistant hash function $(h(\cdot))$" and ECDDHP will result in the following relation:

$$|Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_1} - Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_2}| \leq \frac{q_h^2}{2|hash|} + Adv^{ECDDHP}_{\mathcal{A}}(t). \quad (3)$$

Since all the games have been executed by $\mathcal{A}$, and it is "only remaining for $\mathcal{A}$ to correctly guess a bit to win the game $Game_2^{\mathcal{A}}$", we have,

$$Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_2} = \frac{1}{2}. \quad (4)$$

Eq. (1) gives

$$\frac{1}{2}.Adv^{PBACS-PECIIoT}_{\mathcal{A},ACP}(t) = |Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_0} - \frac{1}{2}|. \quad (5)$$

Eq. (3) leads to the following inequality using Eq. (5):

$$\begin{aligned}\frac{1}{2}.Adv^{PBACS-PECIIoT}_{\mathcal{A},ACP}(t) &= |Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_0} - Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_2}| \\ &= |Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_1} - Adv^{PBACS-PECIIoT}_{\mathcal{A},Game_2}| \\ &\leq \frac{q_h^2}{2|hash|} + Adv^{ECDDHP}_{\mathcal{A}}(t). \quad (6)\end{aligned}$$

Hence, we have the final result: $Adv^{PBACS-PECIIoT}_{\mathcal{A},ACP}(t) \leq \frac{q_h^2}{|hash|} + 2Adv^{ECDDHP}_{\mathcal{A}}(t)$. ■

Remark 4: If $Adv^{PBACS-PECIIoT}_{\mathcal{A},KMP}(t)$ be the advantage of an adversary $\mathcal{A}$ running in polynomial time t in order *to derive the pairwise secret key SK_{GN_j,ES_l} (= SK_{ES_l,GN_j}) established between GN_j and ES_l in a particular session during the key management phase (KMP) for the proposed PBACS-PECIIoT, similar to Theorem 1, we also have:* $Adv^{PBACS-PECIIoT}_{\mathcal{A},KMP}(t) \leq \frac{q_h^2}{|hash|} + 2Adv^{ECDDHP}_{\mathcal{A}}(t)$.

B. INFORMAL SECURITY ANALYSIS

1) REPLAY ATTACK

In PBACS-PECIIoT, during the access control phase described in Section III-B between a smart device SD_i and its gateway node GN_j, the communicated messages Msg_{AC1}, Msg_{AC2}, and Msg_{AC3} have both random nonces and current timestamps. The freshness of the messages is provided by checking the timestamps. Similarly, for the key management among GN_j and its associated edge server ES_l described in Section III-C the communicated messages Msg_{KM1} and Msg_{KM2} are also having random numbers and current timestamps. Thus, the receivers can easily detect the old replayed messages that are re-transmitted by an adversary by validating the attached timestamps of the messages. Therefore, PBACS-PECIIoT is resilient against "replay attack".

2) MAN-IN-THE-MIDDLE(MITM) ATTACK

Suppose an adversary $\mathcal{A}$ eavesdrops the access control request message $Msg_{AC1} = \{RID_{SD_i}, Sig_{SD_i}, RS_{SD_i}, TS_{SD_i}\}$ and tries to send another valid message, say Msg^*_{AC1} to the receiver GN_j. To achieve this goal, $\mathcal{A}$ can select a random number $rs^*_{SD_i} \in Z^*_q$ and timestamp $TS^*_{SD_i}$ on the fly, and then calculate $RS^*_{SD_i} = h(TC_{SD_i} || rs^*_{SD_i} || pr_{SD_i} || RID_{SD_i} || TS^*_{SD_i}) \cdot G_k$. Without knowledge of the temporal credential TC_{SD_i} and permanent secret pr_{SD_i}, $\mathcal{A}$ can not compute valid $RS^*_{SD_i}$ and other valid signature $Sig^*_{SD_i}$ for Msg^*_{AC1}. Similarly, by intercepting the messages Msg_{AC2}, Msg_{AC3}, Msg_{KM1} and Msg_{KM2}, without temporal credentials and permanent secret, $\mathcal{A}$ can modify them on the fly. PBACS-PECIIoT is then resilient against "MiTM attack".

3) IMPERSONATION ATTACKS

Assume an adversary $\mathcal{A}$ plays as a legitimate smart device and tries to communicate with the gateway node by creating a valid message $Msg_{AC1} = \{RID_{SD_i}, Sig_{SD_i}, RS_{SD_i}, TS^*_{SD_i}\}$. For successful attack, $\mathcal{A}$ can pick a random secret $rs_{SD_i} \in Z^*_q$ and timestamp $TS^*_{SD_i}$ to calculate $RS_{SD_i} = h(TC_{SD_i} || rs_{SD_i} || pr_{SD_i} || RID_{SD_i} || TS^*_{SD_i}) \cdot G_k$. Since $\mathcal{A}$ has no idea about secrets TC_{SD_i} and pr_{SD_i}, $\mathcal{A}$ can not compute valid Msg_{AC1}. Similarly, it is also a "computationally impossible task" for $\mathcal{A}$ to construct other valid messages Msg_{AC2}, Msg_{AC3}, Msg_{KM1} and Msg_{KM2}. This means that PBACS-PECIIoT is secure against "smart device, gateway node and edge server impersonation attacks".

4) PRIVILEGED-INSIDER ATTACK

During the registration phase, RA_k does registration of all the entities (SD_i, GN_j, and ES_l) without providing any registration information from the entities. Instead, RA_k deletes all the secrets information (for example, temporal credentials and private keys) after the credentials are stored in the memory of the registering parties after successful registration prior to their deployment in a particular IIoT application. An adversary, being a privileged-insider user of any RA_K, can not then obtain any pre-loaded secret credentials of the deployed entities. Hence, PBACS-PECIIoT is resilient against "privileged-insider attack".

5) PHYSICAL IoT SMART DEVICE CAPTURE ATTACK

Due to existence of an unethical territory, there is a high chance that an adversary $\mathcal{A}$ can physically capture few IoT smart devices SD_i, and extract their stored credentials $\{RID_{SD_i}, TC_{SD_i}, (pr_{SD_i}, Pub_{SD_i}), h(\cdot), E_q(\alpha, \beta), G_k\}$ by applying the "power analysis attacks" [48]. However, the stored credentials are unique and different for all smart devices SD_i. Therefore, it is not possible for $\mathcal{A}$ to establish the session keys between a non-compromised SD_i and its respective GN_j. This circumstance is known as "unconditionally secure against smart device capture attack". As a result, PBACS-PECIIoT is secure against "physical vehicle capture attack".

6) EPHEMERAL SECRET LEAKAGE (ESL) ATTACK

During the access control process between SD_i and GN_j, they establish a common session key $SK_{SD_i,GN_j} = h(DHK_{SD_i,GN_j} || z_{SD_i})$ (= SK_{GN_j,SD_i}) where $DHK_{SD_i,GN_j} = h(TC_{SD_i} || rs_{SD_i} || pr_{SD_i} || RID_{SD_i} || TS_{SD_i}) \cdot RS_{GN_j}$. Similarly, during key management phase between GN_j and ES_l, a common session key is established as $SK_{GN_j,ES_l} = h(DHK_{GN_j,ES_l} || g_j(RID_{GN_j}, RID_{ES_l}))$ (= SK_{ES_l,GN_j}), where $DHK_{GN_j,ES_l} = h(RID_{GN_j} || rs_{GN_{j1}} || TC_{GN_j} || TS_{GN_{j1}} || pr_{GN_j}) \cdot RS_{ES_{l2}}$. In both the scenarios, in order to calculate DHK_{SD_i,GN_j} and DHK_{GN_j,ES_l} the short term (random nonces) and long term secrets (temporal credentials and private keys) are necessary. Since in every session the session keys are unique and distinct, even through a session key is compromised in a particular session it does not affect on the session (secret) keys established in other sessions. PBACS-PECIIoT is then secure against "session-temporary information attack" and it also provides the "perfect forward and backward secrecy" goals at the same time.

7) BLOCK VERIFICATION IN BLOCKCHAIN

In PBACS-PECIIoT, suppose a verifier $\mathcal{V}$ wants to verify a given block, say $Block_k$ in the blockchain. To successfully verify $Block_k$, $\mathcal{V}$ requires computation of "Merkle tree root ($MrkTR$)" on encrypted transactions and "current block hash ($CurBH$)" on all the entities in $Block_k$. If $MrkTR^* = MrkTR$ and $CurBH^* = CurBH$, $\mathcal{V}$ further validates Sig_{Block_k} using "ECDSA signature verification algorithm" with the public key Pub_{ES_l} of ES_l. Since $\mathcal{V}$ verifies all the $MrkTR$, $CurBH$ and Sig_{Block_k}, it is quite hard for an adversary to tamper the block $Block_k$ in the blockchain. If all the validations are successful, $\mathcal{V}$ accepts $Block_k$ as a valid block in the blockchain.

8) TRANSACTION PRIVACY LEAKAGE

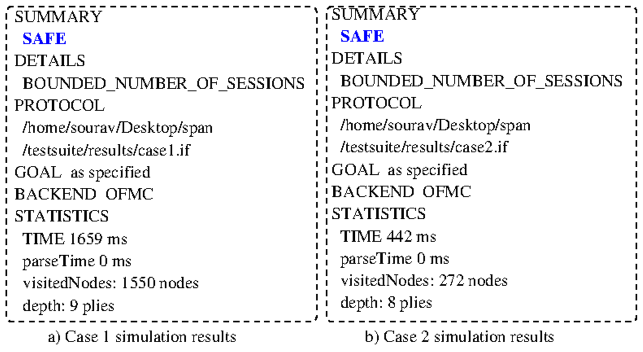
In blockchain, the user behavior can be traceable and it is important to preserve the transaction privacy of the users. A transaction in public blockchain may contain sensitive information and leakage of such critical data is a serious concern. Also, it is important to note that the input transaction should not be linked to its corresponding outputs. The "Bitcoin" and "Zcash" use one-time account to received cryptograms/puzzles. A secret key of user can be used within it so that an attacker cannot derive whether the same transaction contains a user's credential. Moreover, a common wallet may also leakage some vital information of the user. In the proposed PBACS-PECIIoT, due to the private blockchain criteria, the transactions in a block are encrypted with the help of public key of the corresponding edge server Pub_{ES_l}. Therefore, the privacy of the transactions are fulfilled in PBACS-PECIIoT.

9) SELFISH MINING ATTACK

Selfish mining attack is introduced by Eyal et al. in 2014 [62]. In a selfish mining attack [62], an attacker may misuse the computation power and steal the inappropriate rewards from the legitimate miners [63]. The attackers in the selfish mining may aim to retain the large private chain as compared to the public branch so that they can individually hold and dominate to add the additional new blocks. Thus, the selfish miners can obtain more blocks and have a competitive advantage over legitimate miners. This strategy has been extensively mentioned in Bitcoin, but very few attentions have been given to address it. Davidson and Diamond [64] mentioned how the selfish mining can increment the earning of the miners for a larger collection of cryptocurrencies. In PBACS-PECIIoT, we have considered private blockchain and the mining is done by the P2P edge nodes which are treated as semi-trusted. Therefore, selfish mining attack would be hard to perform in the proposed system.

10) BALANCE ATTACK

In this attack, an attacker tries to introduce a delay network communication between a valid range of subgroups consisting of similar mining power capabilities to execute the transactions. However, the miner needs to mine sufficient blocks to assure the subtree of another subgroup is equally essential as compared to the transaction subgroups. Moreover, an attacker can collect the transactions, which are not committed, in order to form a block and it has immense possibility of exceeding the subtree which consists of the transactions. In PBACS-PECIIoT, the individual edge server is connected with each application and it is semi-trusted in the private blockchain. As a result, it is difficult to create a separate chain and mine sufficient blocks into the blockchian. Hence, the balance attack is eliminated in the proposed PBACS-PECIIoT.



```
SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
  /home/sourav/Desktop/span
  /testsuite/results/case1.if
GOAL  as specified
BACKEND  OFMC
STATISTICS
  TIME 1659 ms
  parseTime 0 ms
  visitedNodes: 1550 nodes
  depth: 9 plies
```

a) Case 1 simulation results

```
SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
  /home/sourav/Desktop/span
  /testsuite/results/case2.if
GOAL  as specified
BACKEND  OFMC
STATISTICS
  TIME 442 ms
  parseTime 0 ms
  visitedNodes: 272 nodes
  depth: 8 plies
```

b) Case 2 simulation results

FIGURE 6. Simulation results of PBACS-PECIIoT (cases 1 and 2).

11) SYBIL ATTACK

In this attack, an attacker can damage the reputation system by forging the identities (i.e. fake users' accounts) in the P2P network and use them to achieve the extremely huge domination in the network for making the legitimate entities in minority. Such virtual nodes or illegitimate nodes can then perform like genuine nodes to establish disproportionately huge influence on the P2P network. These may lead to various other attacks, such as "Denial-of-Service (DoS)" and "Distributed Denial-of-Service (DDoS)" attacks. However, it is required to verify or authenticate such nodes and the identities prior to joining the network. In PBACS-PECIIoT, if an edge server behaves like an attacker and tries to perform Sybil attack, it can not dominate the entire network and make the legitimate entities in minority. Therefore, the Sybil attack is resisted in the proposed PBACS-PECIIoT.

V. FORMAL SECURITY VERIFICATION USING AVISPA: SIMULATION STUDY

The "AVISPA tool (Automated Validation of Internet Security Protocols and Applications)" is a push-button software validation tool that provides a "modular and expressive formal language for specifying security protocols and properties, known as the High-Level Protocol Specification Language (HLPSL)" and integrates various back-ends which help in implementing a "variety of automatic analysis techniques ranging from protocol falsification (by finding an attack on the input protocol) to abstraction-based verification methods for infinite numbers of sessions" [65]. AVISPA contains four backends, namely a) "On-the-Fly Model-Checker (OFMC)", b) "Constraint-Logic-based Attack Searcher (CL-AtSe)", c) "SAT-based Model Checker (SATMC)" and d) "Tree Automata based on Automatic Approximations for the Analysis of Security Protocols (TA4SP)". Details on AVISPA tool and its associated HLPSL specifications can be referred to the readers in [66].

The proposed scheme (PBACS-PECIIoT) has been implemented under the HLPSL for two scenarios:

- **Case 1:** It implements the registration and access control phases
- **Case 2:** It implements the registration and key management phases

In both the cases, we have basic roles and the mandatory roles for the session and also for the goal and environment. Since AVISPA implements the DY threat model [50] (as discussed in our threat model in Section II-B), an intruder (i) always takes part of an active participating entity during the communication. Due to this, AVISPA has the ability to check whether a tested security protocol is resilient against "replay attack" and "man-in-the-middle attack". We have simulated both the cases of PBACS-PECIIoT using the "SPAN, the Security Protocol ANimator for AVISPA" [67] under the widely-used OFMC backend. The simulation results demonstrated in Figure 6 clearly show that PBACS-PECIIoT is robust against both replay and man-in-the-middle attacks.

VI. EXPERIMENTS USING MIRACL

We have done the testbed experiments for various cryptographic primitives with the help of widely-accepted "Multiprecision Integer and Rational Arithmetic Cryptographic Library (MIRACL)" [47]. MIRACL is a C/C++ based Crypto SDK which is regarded by the software developers and cryptographers as the "gold standard open source SDK for elliptic curve cryptography (ECC)".

We use the following cryptographic primitives for the testbed experiments. The notations T_h, T_{ecm}, T_{eca}, T_{me}, T_{bp}, T_m, T_a, and T_{senc}/T_{sdec} denote the time required to execute a "one-way cryptographic hash function", an "elliptic curve point (scalar) multiplication", an "elliptic curve point addition", a "modular exponentiation operation", a "bilinear pairing operation", a "modular multiplication over $GF(q)$", a "modular addition over $GF(q)$", and a "symmetric encryption/decryption", respectively. We also considered a non-singular elliptic curve of the type: "$y^2 = x^3 + \alpha x + \beta \pmod q$)" for "elliptic curve point addition and multiplication".

In the following, we consider the following two scenarios:

- The first platform that we have considered is for a server and the environment setting as "Ubuntu 18.04.4 LTS, with memory: 7.7 GiB, processor: Intel$^{\text{ő}}$ Core$^{\text{Ů}}$ i7-8565U CPU @ 1.80GHz $\times$ 8, OS type: 64-bit and disk: 966.1 GB".
- In the second platform, we have considered a smart device under the Raspberry PI 3 implementation where the environment setting is "Raspberry PI 3 B+ Rev 1.3, with CPU: 64-bit, Processor: 1.4 GHz Quad-core, 4 cores, Memory (RAM): 1GB, and OS: Ubuntu 20.04 LTS, 64-bit" [68].

All the experiments are run for 100 times for each cryptographic primitive under both the platforms, and we have then considered the "maximum, minimum and average run-time (in milliseconds) for each cryptographic primitive". The experimental results for various cryptographic primitives

TABLE 3. Experimental results of cryptographic primitives on a server and a Raspberry PI 3 using MIRACL.

Primitive	Average time (ms) under sever	Average time (ms) under Raspberry PI 3
T_{ecm}	0.674	2.288
T_{eca}	0.002	0.016
T_h	0.055	0.309
T_{me}	0.072	0.228
T_m	0.002	0.011
T_a	0.001	0.010
T_{bp}	4.716	32.084
T_{senc}	0.001	0.018
T_{sdec}	0.001	0.014

under a server platform and under the Raspberry PI 3 setting are provided in Table 3.

It is worth noticing that a Raspberry PI uses a "micro SD card" that has the capability to store both the system and data. If we compare a "micro SD card" to the "modern hard drives or solid-state drive (SSD) that are commonly found in computers (Desktops or Laptops)", the operations like reading and writing on the card are then quite slow in case of Raspberry PI [69]. This is why the results reported in Table 3 show the average time difference between the server and Raspberry PI. It is worth noticing that these experimental results are used for our comprative study with respect to computational costs for various schemes including the proposed scheme (see Section VII-A).

VII. COMPARATIVE STUDY

In this section, we provide a detailed comparative study on "security and functionality features", "communication costs" and "computation costs" among the proposed PBACS-PECIIoT and other state-of-art schemes of Li et al. [21], Luo et al. [25], Xue et al. [23], Garg et al. [29].

A. COMMUNICATION COSTS COMPARISON

In PBACS-PECIIoT, to evaluate the communication costs for the access control phase (Case 1) between SD_i and GN_j and for the key management phase (Case 2) among GN_j and ES_l, we consider only communication messages among them. It is assumed that a "random number", an "identity", a "one-way hash function (using SHA-256 hashing algorithm)", an "elliptic curve point $P \in E_q(\alpha, \beta)$" and a "timestamp" are 160, 160, 256, 320, and 32 bits, respectively.

In Case 1 of PBACS-PECIIoT, the communication costs for the messages $Msg_{AC1} = \{RID_{SD_i}, Sig_{SD_i}, RS_{SD_i}, TS_{SD_i}\}$, $Msg_{AC2} = \{RID_{GN_j}, Sig_{GN_j}, RS_{GN_j}, y_{GN_j}, TS_{GN_j}\}$ and $Msg_{AC3} = \{SKV_{SD_i,GN_j}, TS'_{SD_i}\}$ require (256 + 160 + 320 + 32) = 768 bits, (256 + 160 + 320 + 256 + 32) = 1024 bits, and (256 + 32) = 288 bits, which altogether demand 2080 bits. In Case 2 of PBACS-PECIIoT, the messages $Msg_{KM1} = \{RID_{GN_j}, RS_{GN_{j1}}, Sig_{GN_{j1}}, TS_{GN_{j1}}\}$ and $Msg_{KM2} = \{RID_{ES_l}, RS_{ES_{l2}}, Sig_{ES_{l2}}, TS_{ES_{l2}}\}$ needs equally (256 + 320 + 160 + 32) = 768 bits, which altogether require 1536 bits. The

TABLE 4. Comparison of communication costs.

Protocol	No. of messages	Total cost (in bits)
PBACS-PECIIoT (Case 1)	3	2080
PBACS-PECIIoT (Case 2)	2	1536
Li *et al.* [21]	4	5408
Luo *et al.* [25]	2	3040
Xue *et al.* [23]	5	9344
Garg *et al.* [29]	6	4352

TABLE 5. Comparative computational costs analysis.

Scheme	Smart device/User cost	Server cost (GN/ES)
PBACS-PECIIoT (Case 1)	$6T_h + 4T_{ecm} + T_{eca}$ ≈ 11.022 ms	$7T_h + 4T_{ecm} + T_{eca}$ $+tT_m \approx 6.083$ ms
PBACS-PECIIoT (Case 2)	–	$8T_h + 8T_{ecm} + 2T_{eca}$ $+2tT_m \approx 11.836$ ms
Li *et al.* [21]	$5T_{me} + 3T_h$ ≈ 2.067 ms	$4T_{me} + 3T_h + T_{bp}+$ $T_{ecm} + T_{eca} \approx 5.845$ ms
Luo *et al.* [25]	$T_{bp} + T_h$ ≈ 32.393 ms	$3T_{ecm} + 3T_{bp} + 3T_h+$ $T_{eca} + T_{me} \approx 16.409$ ms
Xue *et al.* [23]	$4T_{ecm} + T_{eca} + 5T_{bp}$ $+4T_h + 6T_{senc}/T_{sdec}$ ≈ 170.92 ms	$3T_h + 3T_{me} + 2T_{ecm}$ $+T_{eca} + T_{bp}$ ≈ 6.447 ms
Garg *et al.* [29]	$6T_{ecm} + 8T_h$ ≈ 16.2 ms	$6T_{ecm} + 8T_h$ 4.484 ms

comparative study shown in Table 4 demonstrates that the communication costs for both Case 1 and Case 2 require less costs as compared to other schemes.

B. COMPUTATION COSTS COMPARISON

Assume T_{poly} denotes the time required for "evaluation of an t-degree uni-variate polynomial". Based on the Horner's rule [70], evaluating an "t-degree uni-variate polynomial" requires "t modular multiplications" and "t modular additions", that is, $T_{poly} = tT_m + tT_a$. We have used the average time listed in Table 3 needed for various cryptographic primitives for a server. On the other side, we have used the average time listed in Table 3 needed for various cryptographic primitives for a smart device or user's mobile device under Raspberry PI 3.

In Case 1 of PBACS-PECIIoT, an IoT smart device SD_i requires the computation cost of $6T_h + 4T_{ecm} + T_{eca} \approx$ 11.022 ms and a gateway note GN_j needs the computation cost of $7T_h + 4T_{ecm} + T_{eca} + T_{poly} \approx 6.083$ ms. In Case 2 of PBACS-PECIIoT, both GN_j and ES_l equally need the computation cost of $4T_h + 4T_{ecm} + T_{eca} + T_{poly}$ ≈ 5.918 ms. Here, we have considered $t = 1000$ to support "unconditional security" as suggested by Blundo et al. [57]. The comparative analysis on computation costs in PBACS-PECIIoT for both Case 1 and Case 2 shows that PBACS-PECIIoT needs comparable costs with other existing schemes that are tabulated in Table 5.

C. SECURITY AND FUNCTIONALITY FEATURES COMPARISON

Various "security and functionality features" (FSF_1–FSF_{16}) are considered in comparative study among PBACS-PECIIoT and other schemes (see Table 6). It is evident that PBACS-PECIIoT provides better security features and more functionality attributes as compared to those for other schemes of Li et al. [21], Xue et al. [23] and Luo et al. [25]. Considering the comparative analysis on "communication and computation costs" and "security and functionality features" (FSF_1–FSF_{16}), we can say that PBACS-PECIIoT is much practical to be deployed for PEC in IIoT environment.

Since the fog servers are semi-trusted, the distributed databases with only timestamps can not help to fulfill all the security requirements such as insider attack, device physical capture attack, and most importantly session key security (ESL attack) under the CK-adversary model. However, the proposed PBACS-PECIIoT provides the security features as compared to the existing schemes.

VIII. BLOCKCHAIN IMPLEMENTATION

In this section, we present the practical implementation of our proposed PBACS-PECIIoT, and measure its performance in terms of computational time. The computational time is considered to measure the costs for a block addition and mined in the P2P network. The performance evaluation is considered using a reasonable amount of data for simulation. However, the proposed model can also handle a huge volume of data for an IIoT environment. Many discussions are for scalability issues in blockchain, but in real world scenario the lightning network [71] can be used to handle the high transactions volume. The lightning network is a layer 2 protocol which is specifically used to improve the scalability in blockchain network. The environment was considered for simulation with the following setting: "CPU Architecture: 64-bit, Processor: 2.60 GHz Intel Core i5-3230M, Memory: 8 GB, OS: Ubuntu 18.04.4 LTS".

In each block in the blockchain, we have the block version ($BlkV$), previous block hash ($PreBH$), Merkle tree root ($MrkTR$), industry type (IT_m), timestamp (TS_{ES_l}), creator of block ($CreB_{ID}$), public Key of signer (Pub_{ES_l}), current block hash ($CurBH$), signature (Sig_{Block_k}), whose sizes are taken as 32, 256, 256, 32, 32, 160, 320, 256 and 320 bits, respectively. In addition, each encrypted transaction $E_{Pub_{ES_l}}(Tx_{t_i})$, ($i = 1, 2, \cdots, t_n$), consists of two elliptic curve points and hence, it needs (320+320) = 640 bits. The total block size then turns out to be 1664 + 640 t_n bits.

In order to measure the block generation time in the proposed PBACS-PECIIoT with respect to the block structure mentioned in Figure 4, we have considered the average computational time (in milliseconds) for hash function and ECDSA signature generation under the MIRACL library for a server setting platform (see Table 3). This is because each edge server is resource rich node in the network. Note that the time needed for an ECDSA signature generation is approximately $T_{ecm} + T_h$. In addition, we have also implemented the Merkle tree using SHA-256 hashing algorithm. Based on these results, an edge server can compute the block generation time. In Figure 7(a), a block generation time (in milliseconds) by an edge server is shown for various number of encrypted transactions containing in the block. The results show that the

TABLE 6. Comparison of functionality & security features.

Feature	Li *et al.* [21]	Luo *et al.* [25]	Xue *et al.* [23]	Garg *et al.* [29]	PBACS-PECIIoT
FSF_1	✓	✓	✓	✓	✓
FSF_2	✓	✓	✓	✓	✓
FSF_3	✓	✓	✓	✓	✓
FSF_4	×	×	✓	✓	✓
FSF_5	✓	✓	×	✓	✓
FSF_6	✓	✓	✓	✓	✓
FSF_7	✓	×	✓	✓	✓
FSF_8	N/A	✓	N/A	✓	✓
FSF_9	×	×	×	×	✓
FSF_{10}	×	✓	×	✓	✓
FSF_{11}	×	×	×	×	✓
FSF_{12}	×	×	×	×	✓
FSF_{13}	×	×	×	N/A	✓
FSF_{14}	×	×	×	N/A	✓
FSF_{15}	×	×	×	N/A	✓
FSF_{16}	×	×	×	N/A	✓

Note: FSF_1: "resistant to privileged insider attack"; FSF_2: "replay attack"; FSF_3: "man-in-the-middle attack"; FSF_4: "mutual authentication"; FSF_5: "key agreement"; FSF_6: "device/gateway node impersonation attack"; FSF_7: "resilience against device physical capture attack"; FSF_8: "edge server impersonation attack"; FSF_9: "session key security under the CK-adversary model"; FSF_{10}: "formal security verification using AVISPA tool"; FSF_{11}: "dynamic node addition phase"; FSF_{12}: "support to blockchain-based solution"; FSF_{13}: "transaction privacy leakage"; FSF_{13}: "selfish mining attack "; FSF_{13}: "balance attack "; FSF_{13}: " Sybil attack".
✓: "a scheme is secure or it assists a feature"; ×: "a scheme is insecure or it does not assist a feature"; N/A: "not applicable in a scheme".

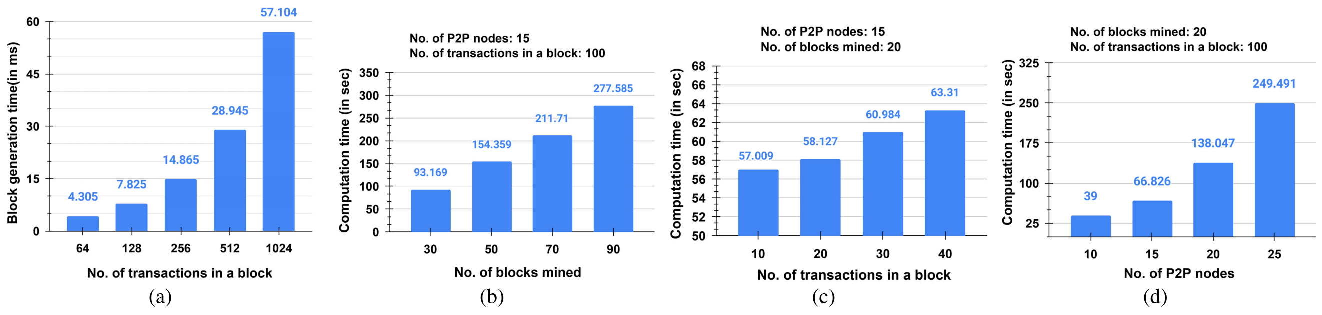


FIGURE 7. (a) Block generation time (in milliseconds) by an edge server, ES_l (b) Blockchain simulation results in Case-I (c) Blockchain simulation results in Case-II (d) Blockchain simulation results in Case-III.

computational time increases when the number of encrypted transactions in a block also increases.

Now, the blockchain implementation has been performed using the node.js language with VSCODE 2019 with the voting-based consensus algorithm explained in Figure 5. The following three cases are taken:

- **Case-I**: We have considered the number of blocks mined versus the total computational time (in milliseconds) with the number of P2P nodes as 15 and the number of transactions per each block as 100. The blockchain simulation outcomes under this scenario are presented in Figure 7(b). It is observed that "as the number of blocks mined increases, the total computational time increases".
- **Case-II**: In this case, we have considered the number of transactions in per block versus the total computational time (in milliseconds). The number of blocked mined is fixed at 20, whereas the number of P2P nodes remains as in Case 1 as 15. Figure 7(c) presents the simulation results. It is worth noticing that the "total computational time increases as the number of transactions per block also increases".
- **Case-III**: In this case, we have considered the number of P2P nodes versus the total computational time (in milliseconds). Moreover, the number of blocked mined is fixed at 20 and the number of transactions in per block is also fixed as 100. We can observe from Figure 7(d) that the "total computational time increases with the increasing number of P2P nodes too".

IX. CONCLUSION AND FUTURE WORK

We proposed a robust and efficient blockchain-based access control enabled blockchain solution for PEC in IIoT deployment (PBACS-PECIIoT). We considered private blockchain scenario due to strictly confidential and private data belonging to each IIoT application. The proposed PBACS-PECIIoT is not only secure against various potential attacks, but it also offers various functionality features. The simulation results using the formal security verification under AVISPA automated software tool demonstrate that PBACS-PECIIoT is secure against passive and active attacks. Finally, a detailed comparative study reveals that PBACS-PECIIoT offers better ''security features'' and more ''functionality features'', requires low ''communication costs'' and comparable ''computational costs'' as compared to existing relevant recent schemes.

Some future works are as follows. We would like to develop of a real testbed experiment for the whole proposed scheme for implementing the access control and key management parts. Next, we would like to apply ''fog computing'', ''multi-access edge computing'', and ''dew computing'' as in [72] to check if it is possible to come out with an efficient blockchain-based access control technique that can significantly reduce the computation cost.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers and the Associate Editor for their invaluable feedback.

REFERENCES

[1] L. D. Xu, W. He, and S. Li, ''Internet of Things in industries: A survey,'' *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[2] (2020). *Industrial IoT (IIoT) Market by Device & Technology*. Accessed: Mar. 2020. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/industrial-internet-of-things-market-129733727.html

[3] Y. Yang, ''A vision towards pervasive edge computing,'' in *Proc. 22nd Int. ACM Conf. Modeling, Anal. Simulation Wireless Mobile Syst.*, Miami Beach, FL, USA, Nov. 2019, p. 1.

[4] J. Sengupta, S. Ruj, and S. Das Bit, ''A comprehensive survey on attacks, security issues and blockchain solutions for IoT and IIoT,'' *J. Netw. Comput. Appl.*, vol. 149, Jan. 2020, Art. no. 102481.

[5] O. Novo, ''Blockchain meets IoT: An architecture for scalable access management in IoT,'' *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1184–1195, Apr. 2018.

[6] C. Zhang, G. Zhou, H. Li, and Y. Cao, ''Manufacturing blockchain of things for the configuration of a data- and knowledge-driven digital twin manufacturing cell,'' *IEEE Internet Things J.*, vol. 7, no. 12, pp. 11884–11894, Dec. 2020.

[7] C. Zhang, G. Zhou, J. Li, F. Chang, K. Ding, and D. Ma, ''A multi-access edge computing enabled framework for the construction of a knowledge-sharing intelligent machine tool swarm in Industry 4.0,'' *J. Manuf. Syst.*, vol. 66, pp. 56–70, Feb. 2023.

[8] M. Castro and B. Liskov, ''Practical Byzantine fault tolerance and proactive recovery,'' *ACM Trans. Comput. Syst.*, vol. 20, no. 4, pp. 398–461, Nov. 2002.

[9] A. K. Das and B. Bruhadeshwar, ''An improved and effective secure password-based authentication and key agreement scheme using smart cards for the telecare medicine information system,'' *J. Med. Syst.*, vol. 37, no. 5, p. 9969, Oct. 2013.

[10] S. Chatterjee and A. K. Das, ''An effective ECC-based user access control scheme with attribute-based encryption for wireless sensor networks,'' *Secur. Commun. Netw.*, vol. 8, no. 9, pp. 1752–1771, Jun. 2015.

[11] D. Mishra, A. K. Das, and S. Mukhopadhyay, ''A secure and efficient ECC-based user anonymity-preserving session initiation authentication protocol using smart card,'' *Peer Peer Netw. Appl.*, vol. 9, no. 1, pp. 171–192, Jan. 2016.

[12] S. Mandal, B. Bera, A. K. Sutrala, A. K. Das, K. R. Choo, and Y. Park, ''Certificateless-signcryption-based three-factor user access control scheme for IoT environment,'' *IEEE Internet Things J.*, vol. 7, no. 4, pp. 3184–3197, Apr. 2020.

[13] M. Wazid, S. Thapliyal, D. P. Singh, A. K. Das, and S. Shetty, ''Design and testbed experiments of user authentication and key establishment mechanism for smart healthcare cyber physical systems,'' *IEEE Trans. Netw. Sci. Eng.*, vol. 10, no. 5, pp. 2697–2709, Sep. 2022.

[14] B. Bera, A. K. Das, W. Balzano, and C. M. Medaglia, ''On the design of biometric-based user authentication protocol in smart city environment,'' *Pattern Recognit. Lett.*, vol. 138, pp. 439–446, Oct. 2020.

[15] A. K. Das, N. R. Paul, and L. Tripathy, ''Cryptanalysis and improvement of an access control in user hierarchy based on elliptic curve cryptosystem,'' *Inf. Sci.*, vol. 209, pp. 80–92, Nov. 2012.

[16] S. Zeadally, A. K. Das, and N. Sklavos, ''Cryptographic technologies and protocol standards for Internet of Things,'' *Internet Things*, vol. 14, Jun. 2021, Art. no. 100075.

[17] A. K. Das, S. Zeadally, and D. He, ''Taxonomy and analysis of security protocols for Internet of Things,'' *Future Gener. Comput. Syst.*, vol. 89, pp. 110–125, Dec. 2018.

[18] S. Roy, S. Chatterjee, A. K. Das, S. Chattopadhyay, N. Kumar, and A. V. Vasilakos, ''On the design of provably secure lightweight remote user authentication scheme for mobile cloud computing services,'' *IEEE Access*, vol. 5, pp. 25808–25825, 2017.

[19] S. Banerjee, V. Odelu, A. K. Das, J. Srinivas, N. Kumar, S. Chattopadhyay, and K. R. Choo, ''A provably secure and lightweight anonymous user authenticated session key exchange scheme for Internet of Things deployment,'' *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8739–8752, Oct. 2019.

[20] B. Bera, A. K. Das, and A. K. Sutrala, ''Private blockchain-based access control mechanism for unauthorized UAV detection and mitigation in Internet of Drones environment,'' *Comput. Commun.*, vol. 166, pp. 91–109, Jan. 2021.

[21] F. Li, J. Hong, and A. A. Omala, ''Efficient certificateless access control for industrial Internet of Things,'' *Future Gener. Comput. Syst.*, vol. 76, pp. 285–292, Nov. 2017.

[22] M. Bilal and S.-G. Kang, ''An authentication protocol for future sensor networks,'' *Sensors*, vol. 17, no. 5, p. 979, Apr. 2017, doi: 10.3390/s17050979.

[23] J. T. Xue, C. X. Xu, and Y. Zhang, ''Private blockchain-based secure access control for smart home systems,'' *KSII Trans. Internet Inf. Syst.*, vol. 12, no. 12, pp. 6057–6078, 2018.

[24] X. Li, J. Peng, J. Niu, F. Wu, J. Liao, and K. R. Choo, ''A robust and energy efficient authentication protocol for industrial Internet of Things,'' *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1606–1615, Jun. 2018.

[25] M. Luo, Y. Luo, Y. Wan, and Z. Wang, ''Secure and efficient access control scheme for wireless sensor networks in the cross-domain context of the IoT,'' *Secur. Commun. Netw.*, vol. 2018, pp. 1–10, Jan. 2018, doi: 10.1155/2018/6140978.

[26] X. Li, J. Niu, M. Z. A. Bhuiyan, F. Wu, M. Karuppiah, and S. Kumari, ''A robust ECC-based provable secure authentication protocol with privacy preserving for industrial Internet of Things,'' *IEEE Trans. Ind. Informat.*, vol. 14, no. 8, pp. 3599–3609, Aug. 2018.

[27] X. Zeng, G. Xu, X. Zheng, Y. Xiang, and W. Zhou, ''E-AUA: An efficient anonymous user authentication protocol for mobile IoT,'' *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1506–1519, Apr. 2019.

[28] A. Esfahani, G. Mantas, R. Matischek, F. B. Saghezchi, J. Rodriguez, A. Bicaku, S. Maksuti, M. G. Tauber, C. Schmittner, and J. Bastos, ''A lightweight authentication mechanism for M2M communications in industrial IoT environment,'' *IEEE Internet Things J.*, vol. 6, no. 1, pp. 288–296, Feb. 2019.

[29] S. Garg, K. Kaur, G. Kaddoum, and K. R. Choo, ''Toward secure and provable authentication for Internet of Things: Realizing Industry 4.0,'' *IEEE Internet Things J.*, vol. 7, no. 5, pp. 4598–4606, May 2020.

[30] L. Zhang, Y. Cui, and Y. Mu, ''Improving security and privacy attribute based data sharing in cloud computing,'' *IEEE Syst. J.*, vol. 14, no. 1, pp. 387–397, Mar. 2020.

[31] R. Xu, J. Joshi, and P. Krishnamurthy, ''An integrated privacy preserving attribute-based access control framework supporting secure deduplication,'' *IEEE Trans. Depend. Secure Comput.*, vol. 18, no. 2, pp. 706–721, Mar. 2021.

[32] H. Tian, X. Li, H. Quan, C.-C. Chang, and T. Baker, ''A lightweight attribute-based access control scheme for intelligent transportation system with full privacy protection,'' *IEEE Sensors J.*, vol. 21, no. 14, pp. 15793–15806, Jul. 2021.

[33] M. Gupta, F. M. Awaysheh, J. Benson, M. Alazab, F. Patwa, and R. Sandhu, ''An attribute-based access control for cloud enabled industrial smart vehicles,'' *IEEE Trans. Ind. Informat.*, vol. 17, no. 6, pp. 4288–4297, Jun. 2021.

[34] Z. Han, X. Li, G. Xu, N. Xiong, E. Merlo, and E. Stroulia, ''An effective evolutionary analysis scheme for industrial software access control models,'' *IEEE Trans. Ind. Informat.*, vol. 16, no. 2, pp. 1024–1034, Feb. 2020.

[35] M. Amoon, T. Altameem, and A. Altameem, ''RRAC: Role based reputed access control method for mitigating malicious impact in intelligent IoT platforms,'' *Comput. Commun.*, vol. 151, pp. 238–246, Feb. 2020.

[36] C. Lin, D. He, X. Huang, K.-K.-R. Choo, and A. V. Vasilakos, ''BSeIn: A blockchain-based secure mutual authentication with fine-grained access control system for Industry 4.0,'' *J. Netw. Comput. Appl.*, vol. 116, pp. 42–52, Aug. 2018.

[37] Y. Ren, F. Zhu, J. Qi, J. Wang, and A. K. Sangaiah, ''Identity management and access control based on blockchain under edge computing for the industrial Internet of Things,'' *Appl. Sci.*, vol. 9, no. 10, p. 2058, May 2019.

[38] G. Yu, X. Zha, X. Wang, W. Ni, K. Yu, P. Yu, J. A. Zhang, R. P. Liu, and Y. J. Guo, ''Enabling attribute revocation for fine-grained access control in blockchain-IoT systems,'' *IEEE Trans. Eng. Manag.*, vol. 67, no. 4, pp. 1213–1230, Nov. 2020.

[39] S. Gao, G. Piao, J. Zhu, X. Ma, and J. Ma, ''TrustAccess: A trustworthy secure ciphertext-policy and attribute hiding access control scheme based on blockchain,'' *IEEE Trans. Veh. Technol.*, vol. 69, no. 6, pp. 5784–5798, Jun. 2020.

[40] Y. Zhang, M. Yutaka, M. Sasabe, and S. Kasahara, ''Attribute-based access control for smart cities: A smart-contract-driven framework,'' *IEEE Internet Things J.*, vol. 8, no. 8, pp. 6372–6384, Apr. 2021.

[41] Y. Nakamura, Y. Zhang, M. Sasabe, and S. Kasahara, ''Capability-based access control for the Internet of Things: An Ethereum blockchain-based scheme,'' in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2019, pp. 1–6.

[42] Y. Liu, Q. Lu, S. Chen, Q. Qu, H. O'Connor, K.-K. Raymond Choo, and H. Zhang, ''Capability-based IoT access control using blockchain,'' *Digit. Commun. Netw.*, vol. 7, no. 4, pp. 463–469, Nov. 2021.

[43] H. Yu, T. Chen, and J. Wang, ''A blockchain-based access control mechanism for IoT,'' in *Proc. 6th Int. Conf. Electron. Inf. Technol. Comput. Eng. (EITCE)*, Xiamen, China, 2023, pp. 25–30.

[44] A. Vangala, A. K. Das, A. Mitra, S. K. Das, and Y. Park, ''Blockchain-enabled authenticated key agreement scheme for mobile vehicles-assisted precision agricultural IoT networks,'' *IEEE Trans. Inf. Forensics Security*, vol. 18, pp. 904–919, 2023.

[45] S. M. Awan, M. A. Azad, J. Arshad, U. Waheed, and T. Sharif, ''A blockchain-inspired attribute-based zero-trust access control model for IoT,'' *Information*, vol. 14, no. 2, p. 129, Feb. 2023. [Online]. Available: https://www.mdpi.com/2078-2489/14/2/129

[46] R. Canetti and H. Krawczyk, ''Universally composable notions of key exchange and secure channels,'' in *Proc. Int. Conf. Theory Appl. Cryptograph. Techn. (EUROCRYPT)*, Amsterdam, The Netherlands, 2002, pp. 337–351.

[47] (2020). *MIRACL Cryptographic SDK: Multiprecision Integer and Rational Arithmetic Cryptographic Library*. Accessed: Apr. 2020. [Online]. Available: https://github.com/miracl/MIRACL

[48] 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.

[49] A. K. Das, ''A random key establishment scheme for multi-phase deployment in large-scale distributed sensor networks,'' *Int. J. Inf. Secur.*, vol. 11, no. 3, pp. 189–211, Jun. 2012.

[50] 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.

[51] H.-F. Huang, ''A novel access control protocol for secure sensor networks,'' *Comput. Standards Interface*, vol. 31, no. 2, pp. 272–276, Feb. 2009.

[52] Y. Zhou, Y. Zhang, and Y. Fang, ''Access control in wireless sensor networks,'' *Ad Hoc Netw.*, vol. 5, pp. 3–13, 2007.

[53] L. Wu, J. Wang, K. R. Choo, and D. He, ''Secure key agreement and key protection for mobile device user authentication,'' *IEEE Trans. Inf. Forensics Security*, vol. 14, no. 2, pp. 319–330, Feb. 2019.

[54] 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.

[55] N. Koblitz, ''Elliptic curve cryptosystems,'' *Math. Comput.*, vol. 48, no. 177, pp. 203–209, 1987.

[56] E. Barker, *Recommendation for Key Management*, document Special Publication 800-57 Part 1 Rev. 4, NIST, Jan. 2016. Accessed: Nov. 2019. [Online]. Available: https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-57pt1r4.pdf

[57] C. Blundo, A. De Santis, A. Herzberg, S. Kutten, U. Vaccaro, and M. Yung, ''Perfectly secure key distribution for dynamic conferences,'' *Inf. Comput.*, vol. 146, no. 1, pp. 1–23, Oct. 1998.

[58] H. Zhang, J. Wang, and Y. Ding, ''Blockchain-based decentralized and secure keyless signature scheme for smart grid,'' *Energy*, vol. 180, pp. 955–967, Aug. 2019.

[59] M. Abdalla, P.-A. Fouque, and D. Pointcheval, ''Password-based authenticated key exchange in the three-party setting,'' in *Proc. Int. Workshop Public Key Cryptogr.*, vol. 3386. Les Diablerets, Switzerland, 2005, pp. 65–84.

[60] M. Bellare, D. Pointcheval, and P. Rogaway, ''Authenticated key exchange secure against dictionary attacks,'' in *Advances in Cryptology—EUROCRYPT 2000*, B. Preneel, Ed. Berlin, Germany: Springer, 2000, pp. 139–155.

[61] C.-C. Chang and H.-D. Le, ''A provably secure, efficient, and flexible authentication scheme for ad hoc wireless sensor networks,'' *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 357–366, Jan. 2016.

[62] I. Eyal and E. G. Sirer, ''Majority is not enough: Bitcoin mining is vulnerable,'' in *Financial Cryptography Data Security*. Berlin, Germany: Springer, 2014, pp. 436–454.

[63] H. Azimy and A. Ghorbani, ''Competitive selfish mining,'' in *Proc. 17th Int. Conf. Privacy, Secur. Trust (PST)*, Aug. 2019, pp. 1–8.

[64] M. Davidson and T. Diamond, ''On the profitability of selfish mining against multiple difficulty adjustment algorithms,'' Cryptology ePrint Archive, Int. Assoc. Cryptologic Res., Tech. Rep. 2020/094, 2020. [Online]. Available: https://ia.cr/2020/094

[65] L. Viganò, ''Automated security protocol analysis with the AVISPA tool,'' *Electron. Notes Theor. Comput. Sci.*, vol. 155, pp. 61–86, May 2006.

[66] AVISPA. (2021). *Automated Validation of Internet Security Protocols and Applications*. Accessed: Jan. 2021. [Online]. Available: http://www.avispa-project.org/

[67] AVISPA. (2021). *SPAN, the Security Protocol ANimator for AVISPA*. Accessed: Jan. 2021. [Online]. Available: http://www.avispa-project.org/

[68] (2020). *Raspberry Pi 3 Model B+*. Accessed: Apr. 2020. [Online]. Available: https://www.raspberrypi.org/products/raspberry-pi-3-model-b-plus/

[69] (2022). *What's the Difference Between a Raspberry Pi and a Computer*. Accessed: Oct. 2022. [Online]. Available: https://raspberrytips.com/difference-raspberry-pi-computer/

[70] D. E. Knuth, *The Art of Computer Programming: Seminumerical Algorithms*, vol. 2, 3rd ed. Boston, MA, USA: Addison-Wesley, 1997.

[71] J. Poon and T. Dryja. (2016). *The Bitcoin Lightning Network: Scalable Off-Chain Instant Payments*. [Online]. Available: https://www.bitcoinlightning.com/wp-content/uploads/2018/03/lightning-network-paper.pdf

[72] S. Namane and I. Ben Dhaou, ''Blockchain-based access control techniques for IoT applications,'' *Electronics*, vol. 11, no. 14, p. 2225, Jul. 2022.

SOURAV SAHA received the B.Tech. degree in computer science and engineering from the Central Institute of Technology, Kokrajhar, India, in 2016, and the M.Sc. (by Research) degree in computer science and engineering from the Indian Institute of Information Technology, Sri City, India, in 2019. He is currently pursuing the Ph.D. degree in computer science and engineering with the Center for Security, Theory and Algorithmic Research, International Institute of Information Technology Hyderabad, Hyderabad, India. His research interests include network security and blockchain technology. He has published 14 papers in international journals and conferences in research areas.

BASUDEB BERA received the M.Sc. degree in mathematics and computing from IIT (ISM) Dhanbad, India, in 2014, the M.Tech. degree in computer science and data processing from IIT Kharagpur, India, in 2017, and the Ph.D. degree in computer science and engineering from the International Institute of Information Technology, Hyderabad, India, in 2022. He was a Postdoctoral Fellow with the Singapore University of Technology and Design (SUTD), Singapore. His research interests include cryptography, network security, and blockchain technology. He has published more than 30 papers in international journals and conferences in research areas.

ASHOK KUMAR DAS (Senior Member, IEEE) received the M.Sc. degree in mathematics, the M.Tech. degree in computer science and data processing, and the Ph.D. degree in computer science and engineering from IIT Kharagpur, India. He is currently a Full Professor with the Center for Security, Theory and Algorithmic Research, IIIT Hyderabad, India, and a Visiting Faculty with the Virginia Modeling, Analysis and Simulation Center, Old Dominion University, Suffolk, VA, USA. His current research interests include cryptography, system and network security including security in smart grids, the Internet of Things (IoT), the Internet of Drones (IoD), the Internet of Vehicles (IoV), cyber-physical systems (CPS), cloud computing, intrusion detection, blockchain, AI/ML security, and post-quantum cryptography. He has authored more than 380 papers in international journals and conferences in the above areas, including more than 320 reputed journal articles. His Google Scholar H-index of 81 and the i10-index of 241 with more than 19,000 citations. He was a recipient of the Institute Silver Medal from IIT Kharagpur. He served as one of the Technical Program Committee Chairs for the first International Congress on Blockchain and Applications (BLOCKCHAIN'19), Avila, Spain, in June 2019, the International Conference on Applied Soft Computing and Communication Networks (ACN'20), Chennai, India, in October 2020, and the Second International Congress on Blockchain and Applications (BLOCKCHAIN'20), L'Aquila, Italy, in October 2020. He has been listed as a Highly Cited Researcher (2022, 2023) from the Web of Science (Clarivate$^{\text{TM}}$) in recognition of the exceptional research performance. He served/serves on the editorial board for IEEE Systems Journal, *Journal of Network and Computer Applications* (Elsevier), *Computer Communications* (Elsevier), *Journal of Cloud Computing* (Springer), *Cyber Security and Applications* (Elsevier), *IET Communications*, *KSII Transactions on Internet and Information Systems*, and *International Journal of Internet Technology and Secured Transactions* (Inderscience).

NEERAJ KUMAR (Senior Member, IEEE) received the Ph.D. degree in CSE from Shri Mata Vaishno Devi University, Katra, India. He was a Postdoctoral Research Fellow with Coventry University, Coventry, U.K. He is currently a Full Professor with the Department of Computer Science and Engineering, Thapar Institute of Engineering and Technology (Deemed to be University) (TIET), Patiala, India. He has published more than 850 technical research papers in leading journals and conferences. His Google Scholar H-index of 111 and the i10-index of 572 with more than 39,900 citations. He is on the editorial board of *ACM Computing Survey*, IEEE Transactions on Sustainable Computing, *IEEE Network Magazine*, *IEEE Communication Magazine*, *Journal of Networks and Computer Applications* (Elsevier), *Computer Communications* (Elsevier), *International Journal of Communication Systems* (Wiley), and *Security and Privacy* (Wiley).

SK HAFIZUL ISLAM (Senior Member, IEEE) received the M.Sc. degree in applied mathematics from Vidyasagar University, Midnapore, India, in 2006, and the M.Tech. degree in computer application and the Ph.D. degree in computer science and engineering from the Indian Institute of Technology [IIT (ISM)] Dhanbad, Jharkhand, India, in 2009 and 2013, respectively, under the INSPIRE Fellowship Ph.D. Program (funded by the Department of Science and Technology, Government of India). He is currently an Assistant Professor with the Department of Computer Science and Engineering, Indian Institute of Information Technology Kalyani (IIIT Kalyani), West Bengal, India. Before joining the IIIT Kalyani, he was an Assistant Professor with the Department of Computer Science and Information Systems, Birla Institute of Technology and Science, Pilani (BITS Pilani), Rajasthan, India. He has more than eleven years of teaching and 13 years of research experience. He has edited four books for the publishers Scrivener-Wiley, Elsevier, and CRC Press. He has authored or coauthored 150 research papers in journals and conference proceedings of international reputes. His research interests include cryptography, information security, neural cryptography, lattice-based cryptography, the IoT and blockchain security, and deep learning. He is a member of ACM. He was a recipient of the University Gold Medal, the S. D. Singha Memorial Endowment Gold Medal, and the Sabitri Parya Memorial Endowment Gold Medal from Vidyasagar University, in 2006. He also received the University Gold Medal from IIT (ISM) Dhanbad, in 2009, and the OPERA Award from BITS Pilani, in 2015. He is an Associate Editor of IEEE Transactions on Intelligent Transportation Systems, IEEE Access, *International Journal of Communication Systems* (Wiley), *Telecommunication Systems* (Springer), *IET Wireless Sensor Systems*, *Security and Privacy* (Wiley), *Array-Journal* (Elsevier), and *Journal of Cloud Computing* (Springer).

YOUNGHO PARK (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electronic engineering from Kyungpook National University, Daegu, South Korea, in 1989, 1991, and 1995, respectively. From 1996 to 2008, he was a Professor with the School of Electronic and Electrical Engineering, Sangju National University, South Korea. From 2003 to 2004, he was a Visiting Scholar with the School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, USA. He is currently a Professor with the School of Electronics Engineering, Kyungpook National University. His research interests include computer networks, multimedia, and information security.