ARTICLE TYPE

Smart Contract Assisted Blockchain based PKI System

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Summary
Public Key Infrastructure (PKI) is a reliable solution for Internet communication. PKI finds applications in secure email, virtual private network (VPN), e-commerce, e-governance, etc. It provides a secure mechanism to authenticate users and communications. The conventional PKI system is centralized, which exposes the infrastructure to many security issues. The digital certificate generation and validation processes in PKI suffer from high latency and inadequate authentication processes. Moreover, it needs enormous time and effort to mitigate the malfeasance of the Certificate Authority (CA). The complexity of employing the traditional key and certificate management increases by enforcing the centralized CA, which can compromise the transaction security. To overcome the aforementioned issues of PKI, three different solutions have been reported in the literature: Log based PKI (LBPKI), Web of Trust (WoT), and blockchain based PKI. The blockchain based PKI achieves more attention as it is the combination of LBPKI and WoT, which serves distributed trust, log of transactions, and constant sized data to verify the identity of users. Motivated by these facts, this article reports a blockchain-based PKI system which has a lighter smart contract and less storage capacity and is also suitable for lightweight applications. The lighter smart contract in our infrastructure uses a threshold value, which validates the limit of one participating node for becoming the CA of any transaction inside the network. This approach can prevent distributed denial of service (DDoS) attacks. This smart contract also checks the signer node address. The proposed smart contract can prevent seven cyber attacks, such as Denial of Service (DoS), Man in the Middle Attack (MITM), Distributed Denial of Service (DDoS), 51%, Injection attacks, Routing Attack, and Eclipse attack. The Delegated Proof of Stake (DPoS) consensus algorithm used in this model reduces the number of validators for each transaction which makes it suitable for lightweight applications. The timing complexity of key/certificate validation and signature/certificate revocation processes do not depend on the number of transactions. The comparisons of various timing parameters with existing solutions show that the proposed PKI is competitively better.

KEYWORDS:
PKI, WoT, LBPKI, Smart Contract, Blockchain based PKI
1 INTRODUCTION

PKI is the primary building block of client-server communication over the internet. PKI defines a set of rules and protocols for the crypto algorithms: encryption, decryption, digital signature, and digital certificate verification process, which are used in secure communication. For server identity authentication, traditional PKI uses a digital certificate which is issued by a trusted third party named as Certificate Authority (CA). This certificate is a data package to identify the identity of the server. The digital certificate is associated with the public key, and it is protected by asymmetric key cryptography. The CA has three primary responsibilities (i) issuing, (ii) revoking (iii) distributing digital certificates. Therefore, it is the most crucial component of PKI. The digital certificate standard, ITU-T X.509 coheres to the public key with the DNS record. The X.509 standard certificate provides a verification method for the private and public keys used for the communication. CA is the only component in PKI to validate a transaction. Traditional PKI system adopts a trusted third party for issuing the digital certificate for every transaction or communication over the internet. There are various third-party CAs reported in the literature, such as Comodo, IdenTrust, DigiCert, Certum, Entrust, etc. The degree of the successful transaction between the client and server depends upon the correctness of the certificate issued by CA. The communications in the aforementioned PKIs rely on the third-party centralized CAs. If the CAs used in Comodo, IdenTrust, DigiCert, Certum, Entrust, etc., become malicious, then the entire communication will be compromised, and it leads to single point failure. Comodo is the first CA which have suffered from cyberattacks. In 2011 it had issued nine fraud digital certificates to various domains. In the same year DigiNotar has issued around 600 fraud certificates to various organizations.

Despite single point failure, the conventional PKI system has several other drawbacks. The conventional PKI does not have any feature to detect compromised CA.

Moreover, the complexity of key generation and key validation processes reduces the performance of the conventional PKI. Considering these threats, servers which are not able to secure their own identities satisfactorily cannot ensure that their communications are not compromised by a deceitful certificate which may cause Man in the Middle attack (MITM).

The malicious certificate issued by a compromised CA can cause severe damage to the transactions of conventional PKI. A malevolent CA like in DigiNotar loses all of its trustworthiness, and it creates a rogue certificate, which makes the entire network at risk. Therefore, the aforementioned statements brief four major concerns of conventional PKI:

- The trust of existing PKI is centralized to Certificate Authority (CA) which can cause single point failure.
- The communications governed by PKI rely on the third-party centralized CAs. The literature has reported many incidents of malicious CAs.
- There are no ways to detect malicious CA.
- The complexity of key generation and key validation processes reduces the performance of the conventional PKI.

Pretty Good Privacy (PGP) is one of the cryptographic solutions against the issues stated above. Unlike traditional CA, PGP gives the opportunity to the participating node to verify the digital certificates of other participating nodes by including their corresponding signature. This attribute creates a trust model where every participating node becomes the verifier for the other. As stated above, the issues of conventional PKI systems are properly addressed by 3 different approaches, such as Web of Trust, Log based, and Blockchain based.

Web of Trust (WoT) is the first approach which addresses the centralization issue of conventional PKI. WoT allows the network participants to choose their own trustworthy certificate provider for transactions. This feature decentralizes the whole infrastructure. The crucial drawback of the WoT is the overhead of the new joinee. The selection process of CA in WoT network is very complicated, which makes it inappropriate for conventional applications. At each successful transaction, the CA increases its trust counter value. Thereafter, for the next transaction, the node chooses a validator which has the highest counter value. The counter value of a new joinee in WoT network is zero. Therefore, the new joinee will never be selected as a validator of any transaction. This issue makes WoT unrealistic for PKI applications.

Public log used in Log Based PKI is one of the solutions which can monitor activities of the CA. The log server will be visible to the entire network. Any illegitimate digital certificate can be identified by this network, and the corresponding CA will be suspended due to its malicious activity. The public log server used in Log Based PKI is always prone to single point failure issue, which is the main disadvantage of this infrastructure. The literature also provides many blockchain based PKIs, which are discussed in Sec. [I.1] and Sec. [I.2].
1.1 | Related Work

In the current section, several PKI solutions are discussed. The discussion includes a PKIs without blockchain technology in Sec. 1.1.1 and blockchain-based PKI solutions in Sec. 1.1.2.

1.1.1 | PKI without Blockchain[14][15][16][17][18][19]

This section discusses about existing PKIs frameworks which have not used blockchain. This type of PKI is further categorized into two groups: log based PKI (LBPKI) and WoT based PKI.  

A  **LBPKI:** Certificate Transparency (CT) in articles maintains a public log of all issued certificates which strives to alleviate the problem of incorrectly issued certificates. The public logs are auditable. Therefore, it is easier for any nodes to check different activities like new certificates generation and certificate deletion. The public logs do not eliminate the risk of certificate misuse. It does not guarantee that the user is able to notice certificate misuse when it occurs.

Proposed Accountable Key Infrastructure (AKI) is used to defend domains and clients from flaws induced by single points of failure. The check and balance method in AKI distributes the trust properly among multiple parties including CAs and domains. Even if the domain key is lost or breached, the AKI executes routine certification processes effectively and gracefully. It was presented as a solution for a public-key validation infrastructure. It selects a set of trusted nodes for validating the entire transactions in the network which decreases the dependency on any one node. Attack Resilient Public-Key Infrastructure (ARPKI) makes all of the certificated-related computations such as (i) certificate issue, (ii) update, (iii) revocation, and (iv) validation processes transparent. ARPKI starts working with 2 different parts. The first part contains two different CAs and the second part contains one Integrated Log Server (ILS) for performing any operations. It ensures that the security will be preserved, even if the $n - 1$ nodes are compromised out of all $n$ number nodes.

**Policert** is a broad log-based and domain-oriented architecture which uses a more secure authentication process for securing the domain’s public keys and an extensive certificate management method for validating the transaction.

B  **WoT based PKI:** LOCALPKI was developed for the Internet of Things applications. In this PKI a local authority binds the public key with the user identity and the certificate is issued by a third-party node or local authority. A third-party entity is used in LOCALPKI to record this binding information and to provide registration updates.

The Notary-based PKI (NBPKI) approach creates a group of trustworthy individuals known as Notarial Authorities (NA). The NA confirms the reliability of a certificate for validating a certain signature at a specified time. The end users depend on NA’s public keys and self-signed certificates for producing and validating signatures. The working principle of NBPKI relies on three different components (i) end-user, (ii) Registration Authority (RA), and the Notarial Authority (NA). The end-user needs to register with RA for signing their transactions. The RA verifies the end-user identity and informs the associated NA. The NA decides the status of the trustworthiness of the end-user based on the information provided by the RA.

1.1.2 | Blockchain based PKI[20][21][22][23][24][25][26][27][28][29][30][31]

This paper primarily addresses 8 attributes to compare different PKI system such as feature, type of blockchain network, blockchain platform, certificate, trust model, off-chain storage, on-chain and time complexity. Table shows the detailed study of different blockchain based PKI systems.

- **Key Feature:** It shows the basic characteristic such as smart contract, CA, public ledge, etc. The blockchain based PKI is developed based on these key features.

- **Blockchain type:** The adopted blockchain network can be either of permissioned or permissionless blockchain. In a permissioned network, the new node can only join when it gets permission from every participating node present in the network whereas, in the permissionless network, new nodes do not require permissions from other nodes exist in the network. Instead of that, it takes permission either from one trusted node or from anyone randomly chosen node.

- **Blockchain Platform:** It shows the platform on which the PKI is implemented. The platform can be on the shelf platform such as Ethereum or a self-developed custom platform. The shelf platforms are publicly available and it needs to be downloaded from a trusted source and configured as per the requirement.

- **Certificate:** It shows the type of certificate used during the PKI development. It can be a X.509 standard or a custom one.
• **Trust Model:** It represents the mechanism for selecting the CA for validating a transaction. One node can choose a trustworthy node or a random node who solves the NONCE first.

• **Consensus Model:** It shows the adopted consensus model during the PKI development.

• **Storage:** The blockchain data can be stored in two forms such as the entire copy of the data will be stored, or the hash function of the block will be stored. There are two categories present for blockchain data storage named as on-chain storage and off-chain storage. On-chain storage allows the node to store the data directly on the blockchain network. Whereas the off-chain storage allows storing the data in a public ledger that is accessible by all other nodes or in a private storage from which that particular node can access it.

• **Time Complexity:** This shows the algorithmic computational complexity in terms of time. It has been taken in big O format as for every PKI all of the defined methods needed to be executed for a successful transaction. So the worst time complexity has been considered for different available blockchain PKI.

### 1.2 Problem Statement and Motivation

The trust of the traditional PKI systems completely depends on third-party CAs. The CA checks the bindings between public keys and entities and then provides digital certificates to those entities. A digital certificate assures that a CA confirms the binding process. There are a very limited number of CAs which are trusted by the modern browser and OS manufacturers. Therefore, this CA-based PKI architecture is considered a centralized infrastructure. The present CA-based PKI architecture, such as CT, AKI, and ARPKI, have adopted many methods to reduce the dependence on the confidence of CA. The primary concern in adopting those PKIs is to avoid the centralization issue of the infrastructure.

Blockchain Based PKIs such as PA-PKI, Block CAM, PB-PKI etc. provide an emerging alternative for conventional PKI system which adopts different features of Log based and WoT approaches. Blockchain based PKI provides an environment for decentralized authentication and validation of transactions in the network. The adoption of different CAs for different transactions in Blockchain based decentralized PKIs eliminates many issues caused by legacy PKIs. The use of different CAs for different transactions increases the fault tolerance capacity of the network and one malicious CA can not sabotage the entire chain. The distributed log in blockchain-based PKI provides a certificate transparency feature which is similar to the certificate transparency (CT) characteristic provided by Google which helps to improve the security of PKIs. The CT allows logging and observing the scope of digital certificates. The examples of blockchain based PKI systems are Namecoin and Emercoin. The Namecoin and Emercoin need enormous storage for the entire blockchain information for validation purposes and they also need to store the entire blockchain copy at the user end. These storage issues have made these blockchain based PKI impractical for real-life applications. The smart contract-based PKI simply dissociates the storage from the validation process where one node does need not to store the entire blockchain copy for validating a transaction. The major lacunas of existing blockchain based PKIs are:

• All the participants in existing blockchain based PKI do not get a fair chance to become CA.

• This complexity of the consensus algorithm in blockchain based PKI makes it inefficient specially for the lightweight application.

• Most of the blockchain based PKIs have concentrated on Denial of Service (DoS) and Man in the Middle Attack (MITM). They have not addressed Distributed Denial of Service (DDoS), 51% attack, Injection attacks, Routing Attack and Eclipse attack.

### 1.3 Contribution

The proposed smart contract-based PKI addresses the challenges of existing blockchain based PKIs. The contribution of the research article is summarized as follows.

• The proposed smart contract of Blockchain based PKI can prevent DoS, DDoS, MITM, 51%, Injection, Routing, and Eclipse attacks. The proposed smart checks the validity of the signer node address and it also imposes a threshold value for becoming CA which gives a fair chance to all the participants to become CA.
| PKI             | Key Feature                                    | Blockchain Type | Blockchain Platform | Certificate Model | Trust Model | Consensus Model | Off-chain Storage | On-chain Storage | Time Complexity |
|-----------------|-----------------------------------------------|-----------------|---------------------|-------------------|-------------|-----------------|-------------------|-----------------|-----------------|
| PA-PKI<sup>10</sup> | Identification and verification of CA          | Permissioned    | Ethereum             | Custom            | WoT         | PBFT            | Private           | Hash            | O(n)            |
| Block-CAM<sup>18</sup> | CA in cross domain verification               | Consortium and Permissioned | Ethereum | X.509 v3  | Hierarchical | NA              | Public Data       | Hash + Data      | O(n²)           |
| BC-TRUST<sup>22</sup>     | Authentication                                | Permission Less | Ethereum             | Custom            | WoT         | NA              | Public Data       | Hash + Data      | –               |
| BLOCK-PGP<sup>23</sup>    | Access Control of Certificate Revocation      | Permissioned    | Ethereum             | X.509             | WoT         | PoW             | Public Data       | NA              | –               |
| PB-PKI<sup>24</sup>       | Public Ledger                                 | Permission Less | Custom              | Custom            | WoT         | NA              | Private Data      | Hash            | O(n)            |
| TTA-SC<sup>25</sup>       | Automating the process of identifying the misconfigured CA | Permission Less | Ethereum             | X.509             | Hierarchical | NA              | Public Data       | Hash + Data      | O(n)            |
| CERT-CHAIN<sup>26</sup>   | CA Trustworthy by using Dual Counting Bloom Filter (DCBF) | Permission Less | Custom              | X.509             | Hierarchical | Dependability rank based | Public Data | Hash | O(n²log(n)) |
| CERT-LEDGER<sup>27</sup> | Certificate Transparency                      | Permission Less | Ethereum             | X.509             | Hierarchical | PBFT            | Public Data       | Hash            | O(log(n))       |
| DB-PKI<sup>28</sup>       | CA                                           | Permission Less | Custom              | Custom            | WoT         | PBFT            | Public Data       | Hash            | O(n²)           |
| IK<sup>29</sup>            | CA trustworthy                                | Permission Less | Ethereum             | X.509             | Hierarchical | NA              | Public Data       | Hash + Data      | O(nlog(n))      |
| FLY-CLIENT<sup>30</sup>   | Transaction Verification for light client     | Permissioned    | Ethereum             | Custom            | Hierarchical | PoS             | Public            | NA              | O(jogn)         |
| BLOCK-QUICK<sup>31</sup>  | Transaction Verification for light client     | Permission Less | Ethereum             | Custom            | WoT         | PoPoW           | Public            | NA              | O(n)            |

- This paper adopted Delegated Proof of Stake (DPoS) consensus algorithm which reduces the number of validators of each transaction. Therefore it reduces the timing complexity which makes it suitable for lightweight applications.
- The proposed PKI system is evaluated based on the two matrices. (i) lapse time of key generation and key validation process and (ii) gas cost of the transaction. The result shows the time complexity of the proposed blockchain based PKI system is efficient compared to existing literature.
1.4 Structure

The rest of the paper is structured in the following manner. Section 2 focuses on the background study for the current work. The proposed blockchain based PKI system based on the smart contract is presented in Sec. 3. The working principle of the proposed PKI system is elaborated in Sec. 4. The proposed model is evaluated based on the gas cost and latency for key generation and validation in Sec. 5. Finally, Sec. 6 represents the conclusion and the future scope of the research work.

2 PRELIMINARIES

Various preliminary elements like the notion of blockchain, smart contracts, and the fundamental concept of PKI are reported in this section.

2.1 Blockchain

In 2008, a whitepaper was released under the pseudonym of "Satoshi Nakamoto" who is considered as the pioneer of the idea of blockchain. Along with the popularity of Bitcoin, blockchain has sparked a lot of interest in academic research and practical applications. The information stored in the immutable ledger of the blockchain can be read by any node inside the network. It combines technologies such as consensus algorithm, smart contract, peer-to-peer (P2P), and encryption to create a new distributed computing paradigm.

Decentralization, immutability, and transparency features of blockchain overcome many problems like high cost, poor efficiency, and single point of failure. Blockchain 1.0, reported by Bitcoin, was created only for the decentralization of cryptocurrency. Since then, many flaws have been addressed in the literature. Non-Turing completeness is an issue, which limits the blockchain’s use in many other fields. Blockchain 2.0 is mostly represented by Ethereum which introduced a smart contract feature. Smart contracts are based on distributed architecture and consensus methods, which allow transactions among users without mutual trust. As a result, smart contracts based blockchain has a lot of potential in existing applications.

2.2 Smart Contract

Externally Owned Addresses (EOA) and smart contract accounts are the two forms of Ethereum accounts. Users own EOA, which includes private key-public key pairs. A smart contract is a program that does not have any key pair and it checks all contract criteria required for that specific application. It includes one or more trigger conditions, such as a specified time or occurrence, and the related reactions, such as a specific transaction or activity. Once it is signed by all parties, the contract is linked to the blockchain data. These contracts are propagated across the P2P network, confirmed by all nodes, and finally deposited in a particular block of the blockchain. Users who know the address of the contract, interface, and other certain details call the smart contract while transactions are started. The miner runs the contract code in the local sandbox environment after getting a call message about the transaction. If the given contract criteria are matched, then all the defined operations for that transaction will be executed. Once the transaction is validated, it is authenticated and inserted into a new block using a consensus procedure. The blockchain also stores the transaction and the modified state along with the status of the participants.

2.3 Ethereum

Ethereum is an open-source platform where the smart contract is the key functionality. It provides a virtual environment where multiple live nodes are deployed to create a blockchain network. Smart contracts are written in Turing complete language known as Solidity which is executed in the Ethereum virtual machine. The smart contract code is publicly available to all participating nodes present in the blockchain network. In the current research work, multiple nodes are deployed with some initial cost and gas using GETH. For every transaction, the node needs to share some gas (G) and each gas has some price (P). So, the total cost (C) in terms of ether (ETH) can be expressed as equation

\[ C = G \times P \] (1)
2.4 PKI

Certificate authority (CA), registration authority (RA), certificate revocation list (CRL), central directory (CD), lightweight directory access protocol (LDAP), and online certificate status protocol (OCSP) are all components of a typical PKI system.44

- **CA**: In the PKI system, CA is a trusted central party. It is in charge of disseminating public keys and issuing certificates using the CA’s private key to validate the transaction. The certificates are kept in a repository for future searches and verification. Normally, CA trust is organized in a chain/tree structure with multiple levels. Root CA (RCA), intermediate CA (ICA), and signing CA (SCA) are all included from top to bottom. The RCA is in dominating position, which may be self-certified. Certificates for other sub-CAs may be issued by root CAs.

- **RA**: The registration of users is the responsibility of RA. When a user requests a certificate, RA must verify the information that the user has submitted. In compact PKI systems, the RA and CA may be the same entity, or a RA might be an ICA or SCA. In large PKI systems, the CA may also select additional trustworthy parties as RAs.

- **CRL**: All revoked certificates signed by the CA are stored in the CRL. In addition, the user must additionally search the CRL to determine the status of a certificate for the validation process.

- **CD**: It is a trustworthy server that is used to store the issued certificate in contrast to the corresponding key.

- **LDAP**: It is a protocol that allows users to quickly access a certificate storage repository which may be CD or CRL.

- **OCSP**: It is a protocol that becomes active when a user request to check the status of a certificate for validation from CRL.

3 PROPOSED WORK

The proposed smart contract based PKI system is implemented in the open-source Ethereum platform known as the Go Ethereum or GETH. The main building blocks of the proposed PKI system are smart contract and Ethereum. Ethereum is used as the platform where the smart contract is the core part of the work.

3.1 Model Description

The proposed PKI system contains three basic modules such as Participant, Smart Contract, Signature, and Revocation. The participant module contains the method to add the attributes of a participating node when it is new to the network. The signature module enables the nodes to sign and validate the keypair. The revocation module allows the node to revoke its own signature so that the corresponding node can resign another transaction.

(A) **New Participant**: The input of this module is the status of the node. If the node is found as a new node of the network, then the 3 attributes: **PID**, **ETH address** and **Keypair** will be set to the status of the new node to participate in the transactions of the network. If a node already exists in the network, the participant module invokes the aforementioned attributes to participate in the transaction. The pseudo-code for this module is presented in algorithm[1] The attributes of the participant module are stated below:

- **PID**: It is a unique random number that can be used to identify a particular node in the network.
- **ETH address**: It is an address provided by the Ethereum blockchain environment which is required during transactions.
- **Keypair**: The private and public key pairs will be generated and assigned to a particular node.

As the current research considers a lighter smart contract, only the PID of that corresponding node is stored after deployment.

(B) **Smart Contract**: The inputs to this module are the **PID**, **RID** and **ETH address**. The **PID** and the **ETH address** of the chosen signer node are compared with the stored **PID** and **ETH address**. If both of the addresses are matched then the **RID** of the signer node will be compared with the defined threshold for that node. The transaction will be allowed only after the successful execution of the above said conditions. The detail pseudocode is reflected in algorithm[2]
(C) **Signature Validation:** This module allows the nodes to sign the transactions of the other nodes. When the node is elected as the signer node, this method will be called with two attributes such as the PID and Expiry. The steps are shown in algorithm 3:

- **PID:** It is the unique number assigned by the Participant method which provides the unique identity.
- **Expiry:** After the validation process the node needs to increase the predefined counter by one to ensure that all of the participant nodes present in the network will get an equal chance to become the transaction lead. This counter value is the maximum number for which one node can be elected as the transaction lead. In the current research work, it is defined in the smart contract to avoid the DDoS attack.

(D) **Revocation:** It is called by the leader node after every transaction. It contains the counter described in the signature module. The node increases the counter by one after every successful transaction. If the counter exceeds the maximum limit defined in the light version of the smart contract, the election process is rejected and the process is reinitiated. Revoke ID or **RID** and Signer ID are two attributes present in this module. The pseudo-code for this module is represented in algorithm 4:

- **RID:** It is a counter which is increased by the leader node after the successful completion of the transaction.
- **Signer ID:** It is the id of the node which is going to validate the transaction.

For certificate revocation and key pair updating process, the participating node needs to broadcast its public key inside the network in the form of a transaction. All the nodes in the network store the data to maintain the distributed trust, therefore, the content of the mined block can only be changed when the maximum number of the participating node agree on the changed value.

### Algorithm 1 New Participant

```
BEGIN TRANSACTION
REQUIRE: Set of Nodes N=[N_1, N_1, N_1, .........., N_n]
PROC PARTICIPANT()
  get N_i.status
  if (N_i.status==FALSE) then
    set PID
    set (PR_key, PB_key)
    set PID.getETHAddress()
    set PID.Limit
  else
    Node N_i is present in the Ethereum private network
  end if
  run CONTRACT()
```

### 3.2 Block structure

[H] Each block has 2 components: block header and list of transactions. Block header has 3 fields: (i) Block root hash, (ii) Hash of the previous transaction, and (iii) Markel Patricia Tree (MPT). Figure 1 represents the structure of block where n is the number of transactions. Here T_i to T_{n-1} are previous validated transactions and T_n denotes the current transaction. H_i denotes the hash value of T_i where i varies from 1 to n. The number of transactions stored in a single block may vary with different blockchain platforms. The size of blocks on certain blockchains, such as Bitcoin, is limited. The ‘genesis block’, or the first block on the blockchain, is noteworthy. It has no hash that refers to a parent block, and it does not allow any mining process. Blocks are issued at fixed intervals. In current Ethereum blockchain new blocks can be released at every 15 seconds interval. The merkel tree has three type of nodes: (i) Leaf Nodes (H_1, H_2, H_3, ... H_n) (ii)Intermediate Nodes (H_1 || H_2,... H_{n-1} || H_n ) and (iii) Root
Algorithm 2 Smart Contract

TRANSACTION PROCESSED
REQUIRE: $N_i.RID, N_i.PID, N_i.ETHAddress$
get Signer.PID
get Signer.RID
get Signer.ETHAddress
if (Signer.PID == $N_i.PID$ and (Signer.ETHAddress == $N_i.ETHAddress$)) then
  if ($N_i.RID \leq N_i.limit$) then
    PROC SIGNATURE
  else
    Maximum Trial is over for the elected signernode. Please select another node
  end if
end if

Algorithm 3 Signature Validation

TRANSACTION PROCESSED
REQUIRE: $N_i.PID, N_i.ETHAddress$
PROC SIGNATURE ()
get Signer.PID
get Signer.ETHAddress
validate(TRANSACTION)
PROC REVOKE()

Algorithm 4 Signature Revocation

TRANSACTION PROCESSED
REQUIRE: $N_i.RID$
if (TRANSACTION == TRUE) then
  RID ++
else
  Transaction is rejected
end if

Nodes ($H_1 || H_2 || ... || H_{n-1} || H_n$). These hashes are also used as the node’s reference key. The leaf node ($L_i$), intermediate node ($I_i$), and root node (R) of the MPT are defined as in equations (2), (3), and (4) respectively.

$$L_i = H_i = hash(x_i), \{i \in 1, 2, 3, 4, ..., m\} \quad (2)$$

$$I_i = \{H_i || H_{i+1}\} \quad (3)$$

$$R = \{H_1 || H_2 || ... || H_N, N = Depth of MPT\} \quad (4)$$

3.3 Delegated Proof of Stake Consensus Mechanism

The Delegated Proof of Stake (DPoS)\textsuperscript{45} consensus algorithm is a variance of the PoS mechanism which improves scalability and efficiency by lowering and limiting the number of validators on the network. It was designed to address the issue scalability trilemma\textsuperscript{24}. In blockchain terminology, the more number of transactions per unit time refers to more scalability. As per the blockchain trilemma, more scalability may cause more challenges for security and decentralization features. In DPoS, token holders do not work on the validity of the blocks directly; instead, they choose delegates to validate transactions on their
There are typically 21–100 designated delegates in a DPoS system. The chosen delegates are rotated regularly and the nodes order the delegates to present their blocks. When there are fewer delegates, it is easier to allocate one validator and time slot for each transaction. If the delegates consistently miss to validate transactions or blocks, it will cause erroneous transactions. As a result, the token holders vote them out and replace them with another delegate chosen by the token holders.

4 | WORKING PRINCIPLE

Once it receives the transaction request, the participant module starts its execution to check the status of the node. If the node is found as a new node, the required parameters such as the *PID, ETH Address, keypair*, and a threshold value for *RID* will be specified for the node. This *RID* is incremented by one in each revocation call and once it reaches to the threshold the *PID, ETH Address* and *keypair* of the node will be reset. The *PID* and *ETH Address* identify a particular node at any time uniquely.

After the successful execution of the participant module, the smart contract is invoked. Thereafter the *PID* of the selected signer node is compared with the stored *PID*. If both *PIDs* are matched further execution will be allowed otherwise the process will be aborted. Then the *RID* counter will be compared with its threshold limit. If the *RID* exceeds the given threshold, the transaction will be aborted immediately otherwise, the signature module will be invoked. The adoption of the smart contract in our methodology helps the network to deal with the DDoS and MITM attacks by verifying the node id and checking the limit respectively.

The signature module allows the selected signer node to validate the transaction by verifying the public key. The Signature module allows that particular node to validate the transaction which completes the smart contract verification phase.

After every successful transaction, the signature revocation module is invoked where the signer node increments its *RID* value by 1 and validates the transaction. Figure 2 represents the workflow of the proposed work.

5 | IMPLEMENTATION & COMPARISON

The proposed work can be evaluated by its performance and comparison with existing literature.

5.1 | Implementation

The proposed work is implemented in the open-source Ethereum virtual machine *GETH*. To invoke the smart contract, the *Solidity v0.4.24* scripting language is used along with the *GANACHE truf file* suit. The *truf file* suit deploys the developed smart contract in the blockchain environment. Initially, the Gas limit of the network is set as 4000000 and all created nodes have 100*ETH* in their account. The experiment is carried out with a Windows 10 OS, 8 GB RAM, 1 TB HDD, and *Intel i5* processor with a 2.8GHz clock speed machine.
FIGURE 2 Workflow of proposed Blockchain based PKI

5.2 Performance

The performance of the proposed PKI system is evaluated using the latency and gas utilization during the transaction. Figure 3 shows the latency vs the number of nodes graph for key generation and key validation process. The proposed model is tested with 100 nodes where latencies of key generation and key validation process reach to 60 seconds and 80 seconds respectively which is suitable for realistic applications of PKI. Figure 4 shows gas utilization vs the number of transaction graph where the average gas cost for each transaction is approximately $10 \times 10^4$. Table 2 shows the gas used by the different modules of the developed PKI system for doing one transaction.

| Method Name      | Gas Utilized For Initialization | Gas Utilized For Transaction |
|------------------|---------------------------------|------------------------------|
| Participant      | 33781                           | 17484                        |
| Signature        | 42856                           | 13752                        |
| Revocation       | 19798                           | 9689                         |
| Smart Contract   | 194837                          | 32675                        |

5.3 Time Complexity Evaluation

There are four executable modules present in the developed blockchain based PKI system, namely *participant*, *signature*, *revoke*, and *smart contract*. Among these four modules, the time complexity of *participant* and *smart contract* module is $O(n)$,
whereas the time complexity of signature and revoke modules are $O(1)$. Here $n$ is the number of transactions committed to the procedure in the network. Multiple transaction requests may be raised in the case of participant and smart contract module resulting in the worst time complexity of these two modules as $O(n)$. While there is no communication in the other two modules: signature and revoke and also, no acknowledgment messages are issued to the transaction initiator. The signature and revoke modules allow the chosen signer node (by smart contract module) to sign the transaction and make an increment of $RID$. So these two procedures do not generate any transaction messages, which results in constant time complexity of $O(1)$. Implementing the DPoS consensus mechanism results in a run time complexity of $O(log(n))$. The time complexity of the whole system is $O(n + logn)$. The time complexity of the proposed model is compared with the different exiting models in Table 3.

### TABLE 3 Module wise Time Complexity Comparison with different existing models

| Blockchain based PKI | Key/ Certificate Generation | Key/ Certificate Validation | Signature/ Certificate Revocation |
|-----------------------|-----------------------------|-----------------------------|----------------------------------|
| PA-PKI                | $O(n^2)$                    | $O(n)$                      | $O(n)$                           |
| CERT-CHAIN            | $O(n^2)$                    | $O(log(n))$                 |                                  |
| CERT-LEDGER           | $O(log(n))$                 | $O(n^2)$                    |                                  |
| DB-PKI                | $O(n^2)$                    | $O(n^2)$                    |                                  |
| FLY-CLIENT            | $O(n^2)$                    | $O(logn)$                   |                                  |
| BLOCKQUICK            | $O(n)$                      | $O(n)$                      |                                  |
| Proposed System       | $O(n)$                      | $O(1)$                      | $O(1)$                           |

5.4.1 Critical Analysis

This work addresses various limitations of the existing PKI solutions including PKI without blockchain stated in Sec. 1.1.1 and PKI with Blockchain stated in Sec. 1.1.2. The PKI provided in only focuses on making the issued certificate visible to the network participants but does not have any circumstances to avoid the single point of failure (SPoF) limitation. In AKI the ILS is responsible to store the certificate issued by CA and the ILS will be updated at a given time interval even CA becomes untrusted. This becomes the key limitation along with SPoF as it is using a centralized CA to issue the certificate. ARPKI tries to solve the synchronization issue of AKI but it still depends upon a trusted CA to issue the certificate. The unavailability of the CA verification process makes it tough to adopt ARPKI as a preferred solution. The approach in PoliCert provides a centralized way to detect the log misbehavior which is again pruned to SPoF issue. LOCALPKI was created for usage in the context of IoT, where the local authority is in charge of utilizing the public key to verify the user's identity. The certificates issued by the local authority are stored by a third party, which are trimmed to SPoF. In NBPKI RA is in charge of authenticating the
user’s identification, and the NA maintains the user’s status as trusted or untrusted based on the RA’s decision. The malicious RA has the potential to compromise the system’s integrity.

The PA – PKI in article 21 uses Practical Byzantine Fault Tolerance (pBFT) consensus model which allows a certain number of faulty nodes. If the number of faulty nodes exceeds that certain limit, the whole network will be reset. Moreover, pBFT consensus mechanism used in PA – PKI of article 21 and DB – PKI of article 22 is prone to the Sybil attack. The Block – CAM in article 23 has used the consortium blockchain platform for developing their PKI. The major limitation of using this platform is making the entire system semi-centralized since the consensus is managed by a certain number of participating nodes. Thus, it deviates from the decentralization concept of blockchain. Our proposed model is completely decentralized to all existing nodes in the network. The transactions of BCT RS T in 24, depend upon the degree of trustworthiness of a participating node. Once the node is declared as the trusted one, then every node in the same network has to consider that node as the same. Moreover, all the transactions made by that node are also considered as valid transactions which may cause integrity loss and many other cyber threats. In our model verification is done on every transaction where node identity already padded, it does not verify only such node based identity. This feature makes our model more secure compared to 25. The implementation of PGP of both server and client-side participating nodes in BlockPGP 26 causes heavy computational overhead which is the major drawback of such PGP based infrastructure.

In the case of PB PKI 24, the transactions are stopped if any anonymous node requests to join the network. When new anonymous node requests to join the network, the entire network is disrupted until the joining request is processed. The developed PKI TTA SC in article 27 suffers from the loss of control issue over the blockchain network if it loses the key pair of the lead node under some cyber attacks. The DDoS attack to a particular lead node can make the system destabilized. The CERT CHAIN in article 27 uses dependability rank based consensus algorithm where the elected CA was responsible for increasing the trustworthy degree. Depending upon the degree of trustworthiness the node will be elected as CA. Thus, a DoS attack on the particular CA can cause damage in further transactions. It also uses the PBFT consensus algorithm which may cause a Sybil attack. In the CERT LEDGER of the article 27, the CA is responsible for publishing the revoked data after every transaction. Thus, a DoS attack on that particular CA can disrupt the entire network. The developed PKI I KP in article 28 depends on the bitcoin’s language script which becomes hard to implement. The transaction process in I KP depends on the trustworthiness of the CA and if the CA is misconfigured then all transactions within the network will be discarded. The FLY CLIENT of article 28 does not use an authentication process to validate the participating node identification. So, the developed PKI is prone to MITM attack. In BLOCK QUICK of the article 31, the malicious block can only be detected by using the consensus group score. So, for a single malicious node, the whole branch will be discarded which will reduce the efficiency of the network.

5.5 | Attack and Defense

The primary feature of the developed blockchain based PKI is the smart contract where the conditions such as the validity and threshold of the signer node are verified. The smart contract is solely responsible to allow the signer node to validate the key pair of requested nodes otherwise the nodes will be rejected. This feature avoids the DDoS and MITM attacks for the developed PKI. The proposed permissionless blockchain environment on the GETH platform adopts the trust model of WoT where nodes are allowed to choose their own CA. In the hierarchical trust model, the processing power required to calculate the NONCE is high, whereas WoT does not require any NONCE calculation. The NONCE calculation can prevent MITM attacks. However, we have avoided it intentionally in our PKI to make it lighter compared to existing literature. From the storage point of view, only the hash value of each node is considered for the on-chain storage and the entire data is considered for the off-chain storage. Different attacks addressed in the current blockchain based PKI are reflected in Table 4. Table 5 reflects the various attack resistance comparison of the proposed model in contrast to other existing blockchain PKI models.

6 | CONCLUSION

The proposed research work identifies several issues of conventional PKI and blockchain based PKI. In this regard, this work proposes a blockchain based PKI which is assisted by a smart contract and DPoS consensus algorithm. This work explores different existing solutions such as log based PKI, web of trust (WoT), and the blockchain based PKI system to deal with the various limitations and cyber threats of existing PKIs. The primary objective of this work is to create a blockchain based decentralized public key infrastructure which takes advantage of both the blockchain transparency and the web of trust model. The inclusion
TABLE 4 Different Threats & Its Defence

| Attack   | Basic Definition                                                                 | Prevention Mechanism                                                                 | Sustainability |
|----------|----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|----------------|
| DoS      | The elected CA may initiate a huge number of transactions.                       | The proposed model defines a threshold for every node for becoming a CA and the implemented smart contract checks the given threshold with the RID. If the RID exceeds the threshold, the participation of CA will be rejected (see. Algo. 2). | Moderate       |
| DDoS     | Multiple elected CAs overload the network by initiating multiple transactions.    | The nodes in the network can become a CA if the RID is less compare to the given threshold. (Algo. 2) | Moderate       |
| MITM     | An intermediate node may try to modify the transaction. This can be done in two ways such as modifying the content or modifying the sender/receiver node address. | Hash prevents content modification. The node verification process at the smart contract resolves the address violation part. | low            |
| 51%      | It is an attack on blockchain where attackers acquire the control of more than 50% of the network’s node address and cause faulty transactions. | Before initiating the transaction, the node identity will be checked and only the active node of the network will be allowed for the transaction. (Algo. 1) | low            |
| Injection| Injecting multiple unknown nodes to access the data                              | The adopted WoT does not allow the joining of a random node in the network.          | low            |
| Routing  | Tampering the data during the transaction                                           | Hashing is used to secure the information.                                          | low            |
| Eclipse  | The attacker may have a distributed botnets for replacing the actual node addresses by the false addresses. | For every transaction, the PID will be checked for availability and WoT model restricts random joining of nodes | low            |

TABLE 5 Attack resistance comparison

| PKI       | DoS | DDoS | MITM | 51% | Injection | Routing | Eclipse |
|-----------|-----|------|------|-----|-----------|---------|---------|
| PA-PKI    | ✗   | ✗    | ✔    | ✗   | ✗         | ✗       | ✗       |
| Block-CAM | ✔   | ✔    | ✔    | ✗   | ✗         | ✗       | ✗       |
| BC-TRUST  | ✔   | ✔    | ✔    | ✗   | ✗         | ✗       | ✗       |
| BLOCK-PGP | ✗   | ✗    | ✔    | ✔   | ✗         | ✗       | ✗       |
| PB-PKI    | ✔   | ✗    | ✔    | ✗   | ✗         | ✗       | ✗       |
| TTA-SC    | ✗   | ✗    | ✔    | ✔   | ✗         | ✗       | ✗       |
| CERT-CHAIN| ✗   | ✗    | ✔    | ✔   | ✗         | ✗       | ✗       |
| CERT-LEDGER| ✗  | ✗    | ✔    | ✔   | ✗         | ✗       | ✗       |
| DB-PKI    | ✗   | ✗    | ✔    | ✔   | ✗         | ✗       | ✗       |
| IKP       | ✗   | ✗    | ✔    | ✔   | ✗         | ✗       | ✗       |
| FLY-CLIENT| ✗   | ✗    | ✔    | ✔   | ✗         | ✗       | ✗       |
| BLOCKQUICK| ✗   | ✗    | ✔    | ✔   | ✗         | ✗       | ✔       |
| Proposed System | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |

of smart contracts along with participant, signature and revoke modules in our work achieves the aforementioned features. The primary role of the adopted smart contract is used to validate the identity of the signer node and to check the threshold value for
becoming CA. The DPoS consensus algorithm used in our PKI reduces the timing complexity of the transactions which makes our PKI affordable for lightweight applications. The performance of the proposed PKI system is evaluated based on the latency of the key generation, key validation, and signature revocation process. The gas utilization on the Ethereum platform is minimal for the initialization process and transactions. The proposed PKI can prevent DoS, DDoS, MITM, 51%, Injection, Routing and Eclipse attacks. The developed smart contract used in our blockchain based PKI system is lighter to address the issue of storage limitation.

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