US010204339B2

(12) **United States Patent**
Madisetti et al.

(10) **Patent No.: US 10,204,339 B2**
(45) **Date of Patent: Feb. 12, 2019**

(54) **METHOD AND SYSTEM FOR BLOCKCHAIN-BASED COMBINED IDENTITY, OWNERSHIP, INTEGRITY AND CUSTODY MANAGEMENT**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/118,599**

(22) Filed: **Aug. 31, 2018**

(65) **Prior Publication Data**

US 2018/0374091 A1 Dec. 27, 2018

Related U.S. Application Data

(63) Continuation of application No. 16/032,480, filed on Jul. 11, 2018, now Pat. No. 10,121,143, which is a (Continued)

(51) **Int. Cl.**

G06Q 20/38	(2012.01)
H04L 9/32	(2006.01)
H04L 9/06	(2006.01)
H04L 9/14	(2006.01)
G06Q 20/36	(2012.01)

(Continued)

(52) **U.S. Cl.**
CPC ***G06Q 20/38215*** (2013.01); ***G06Q 20/065*** (2013.01); ***G06Q 20/367*** (2013.01); ***H04L 9/0637*** (2013.01); ***H04L 9/14*** (2013.01); ***H04L 9/30*** (2013.01); ***H04L 9/3242*** (2013.01); ***H04L 9/3247*** (2013.01); ***H04L 9/3263*** (2013.01); *H04L 2209/56* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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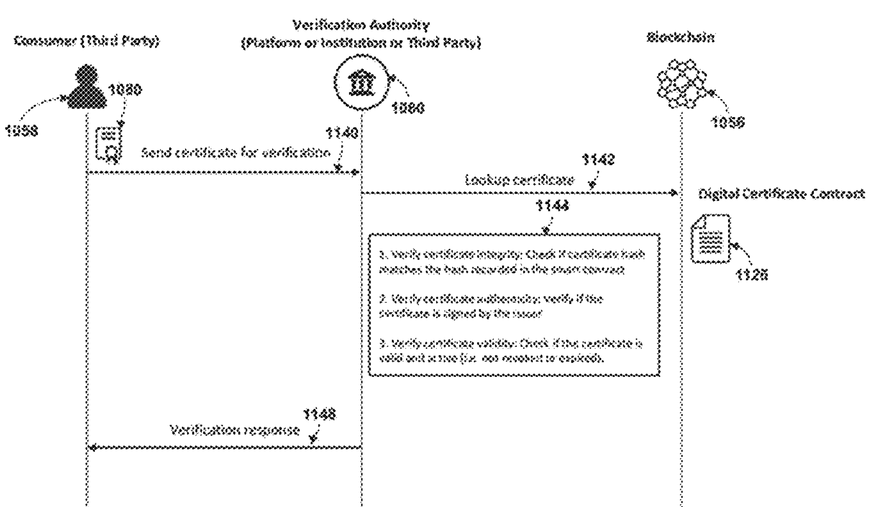
Primary Examiner — Michael R Vaughan
(74) *Attorney, Agent, or Firm* — Daniel C. Pierron; Widerman Malek PL

(57) **ABSTRACT**

A method of issuing blockchain-based digital certificates including receiving from a user hashed user identification information and object information, recording to a digital certificate smart contract deployed at a digital certificate smart contract address on a blockchain network the hashed user identification information and object information and a timestamp of when the hashed user identification information and the object information were received, defined as a received timestamp, signing the digital certificate smart contract with an issuer signature, performing a user identity verification process to confirm a user identity, the user identity verification process, and upon confirming the user identity, generating a combination certificate configured to verify the user's ownership of an object associated with the object information.

17 Claims, 22 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/863,128, filed on Jan. 5, 2018, now Pat. No. 10,102,526.

(60) Provisional application No. 62/582,422, filed on Nov. 7, 2017, provisional application No. 62/479,966, filed on Mar. 31, 2017.

(51) **Int. Cl.**
G06Q 20/06 (2012.01)
H04L 9/30 (2006.01)

(56) **References Cited**

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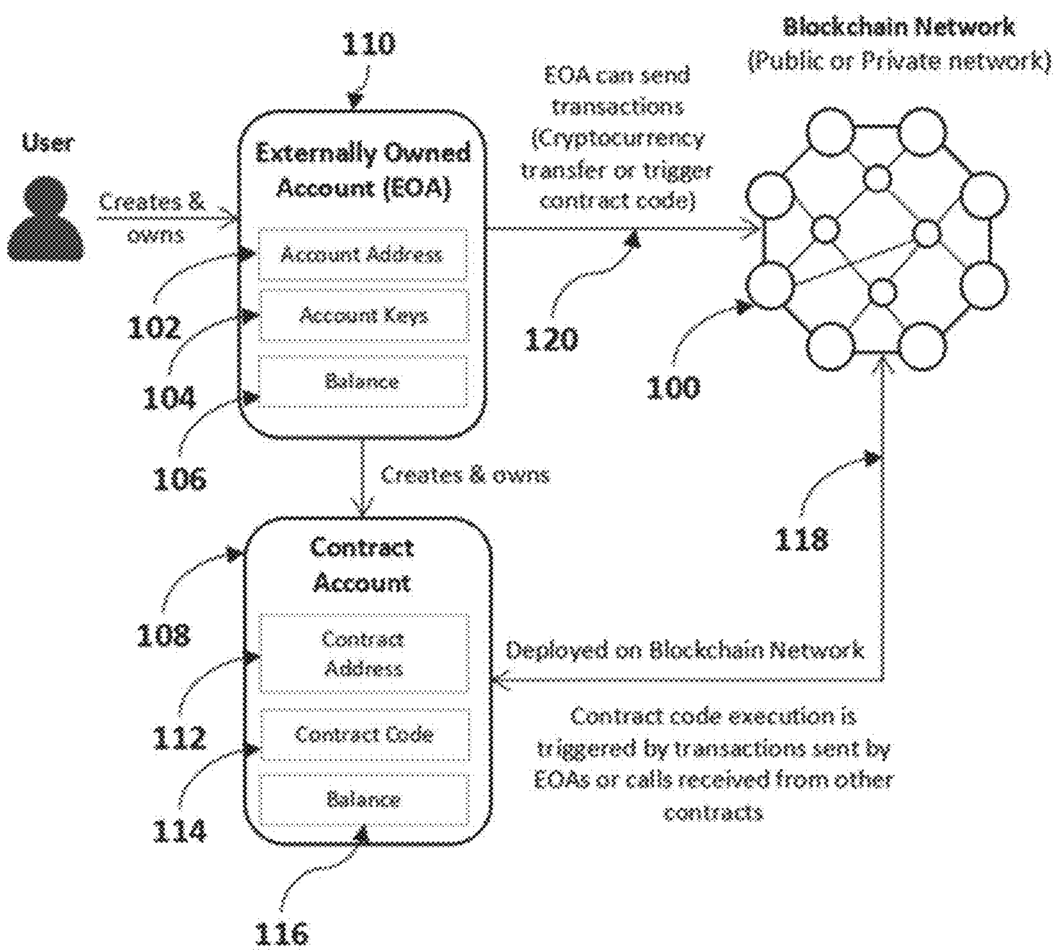


Blockchain Network
(Public or Private network)
User
Creates & owns
Externally Owned Account (EOA)
Account Address
Account Keys
Balance
EOA can send transactions (Cryptocurrency transfer or trigger contract code)
110
102
104
106
120
100
Creates & owns
Contract Account
Contract Address
Contract Code
Balance
108
112
114
116
118
Deployed on Blockchain Network
Contract code execution is triggered by transactions sent by EOAs or calls received from other contracts

FIG. 1

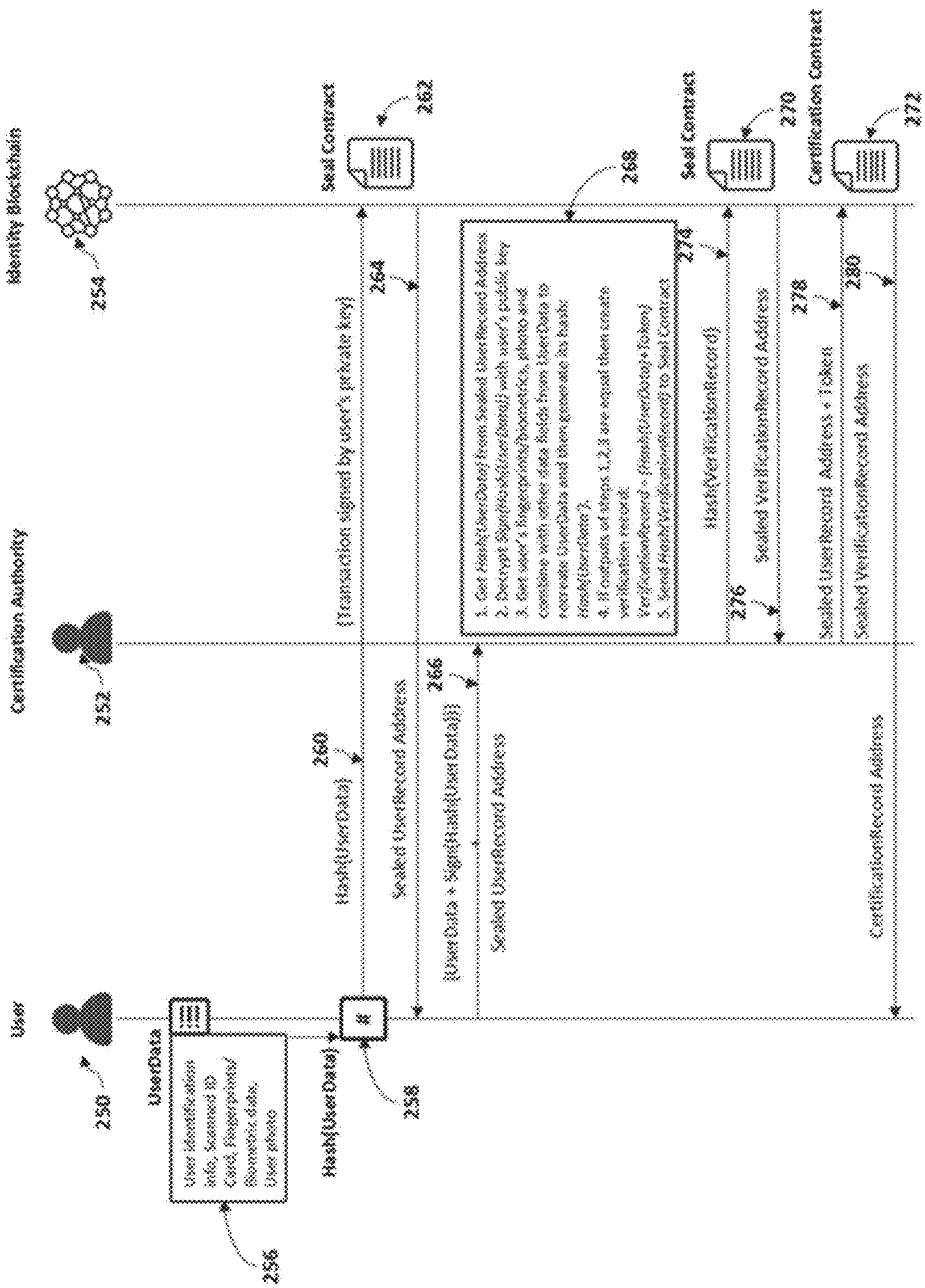

User
Certification Authority
Identity Blockchain
250
252
254
UserData
256
Hash(UserData)
258
260
Hash(UserData)
(Transaction signed by user's private key)
262
Seal Contract
264
Sealed UserRecord Address
266
{UserData + Sign(Hash(UserData))}
Sealed UserRecord Address
268
Hash(VerificationRecord)
274
270
Seal Contract
Sealed VerificationRecord Address
276
278
Sealed UserRecord Address + Token
272
Certification Contract
280
Sealed VerificationRecord Address
CertificationRecord Address

FIG. 2

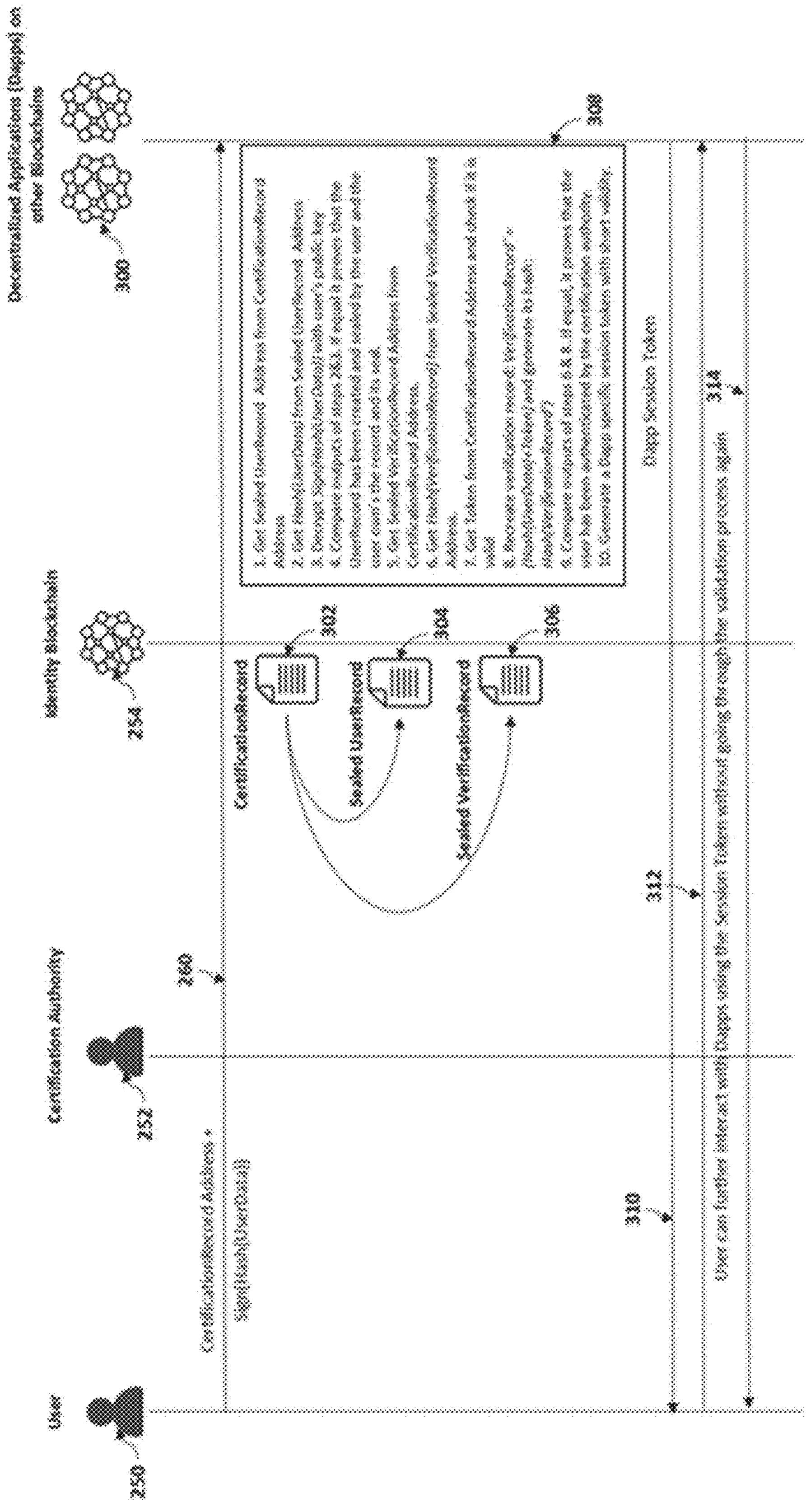

User
250
Certification Authority
252
Identity Blockchain
254
Decentralized Applications (Dapps) on other Blockchains
300
260
CertificationRecord
Sealed UserRecord
Sealed VerificationRecord
302
304
306
308
Dapp Session Token
310
312
314
User can further interact with Dapps using the Session Token without going through the validation process again

FIG. 3

350

```
contract Seal {
        address public owner;
        uint public hashedData;

        function Seal(uint _hashedData) {
                owner = msg.sender;
                hashedData = _hashedData;
        }
}
```

352

```
contract Certification {
        address public owner;
        address public sealedUserRecordAddress;
        address public sealedVerificationRecordAddress;
        uint public token;
        uint public tokenExpires;

        function Certification(address _sealedUserRecordAddress,
                        address _sealedVerificationRecordAddress
                                uint _token, uint _tokenExpires) {
                owner = msg.sender;
                sealedUserRecordAddress = _sealedUserRecordAddress;
                sealedVerificationRecordAddress = _sealedVerificationRecordAddress;
                token = _token;
                tokenExpires = _tokenExpires;
        }
}
```

FIG. 4

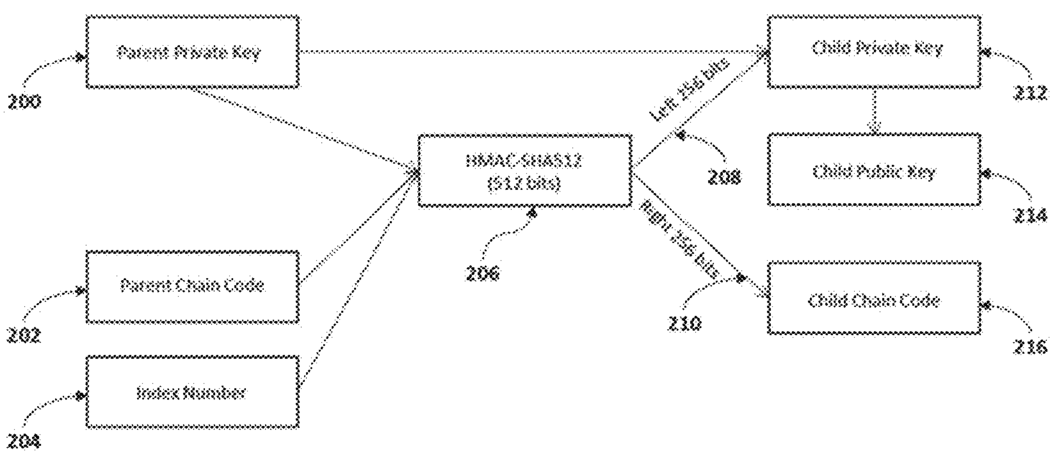


FIG. 5

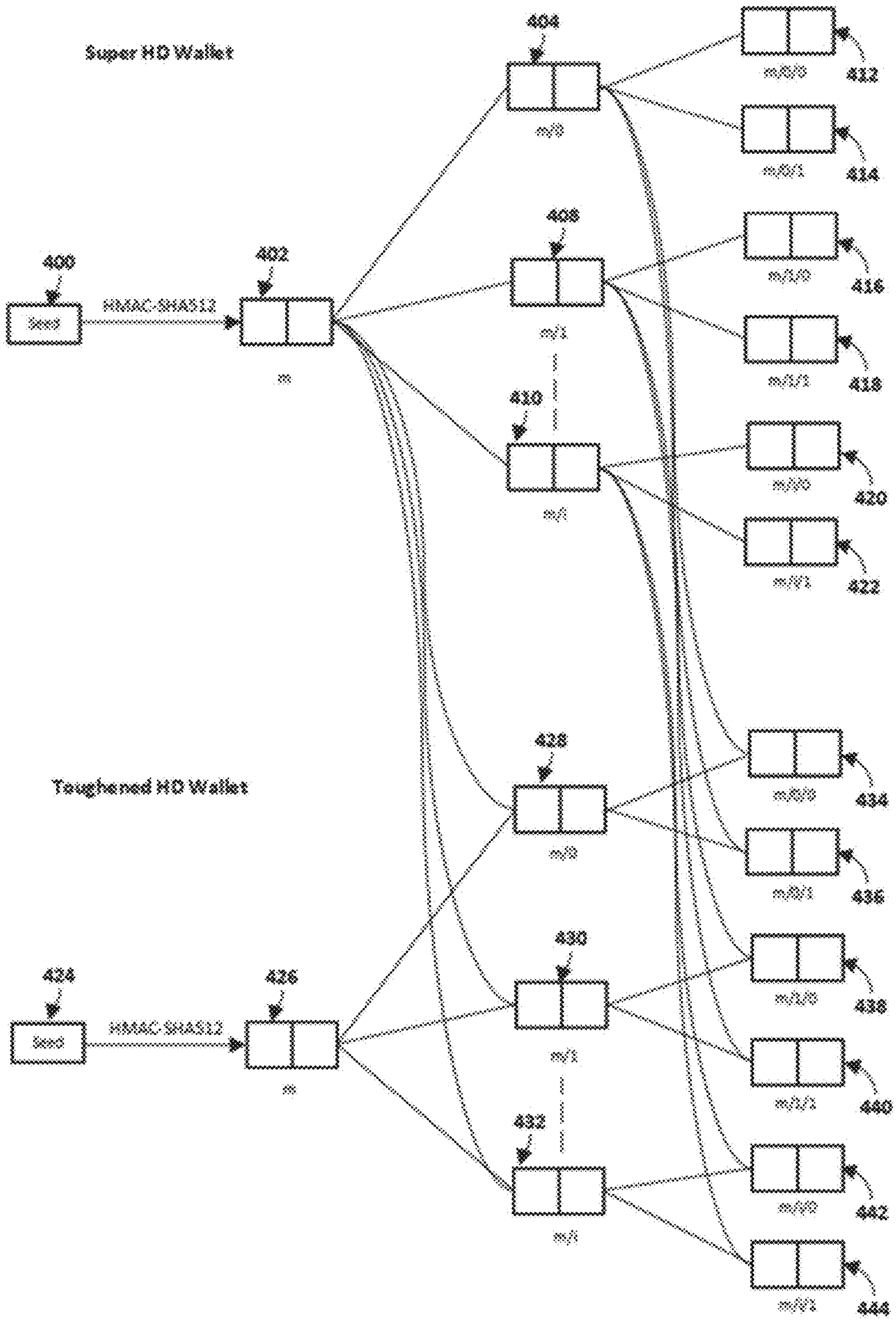

Super HD Wallet
400
Seed
HMAC-SHA512
402
m
404
m/0
408
m/1
410
m/i
412
m/0/0
414
m/0/1
416
m/1/0
418
m/1/1
420
m/i/0
422
m/i/1
Toughened HD Wallet
424
Seed
HMAC-SHA512
426
m
428
m/0
430
m/1
432
m/i
434
m/0/0
436
m/0/1
438
m/1/0
440
m/1/1
442
m/i/0
444
m/i/1

FIG. 6

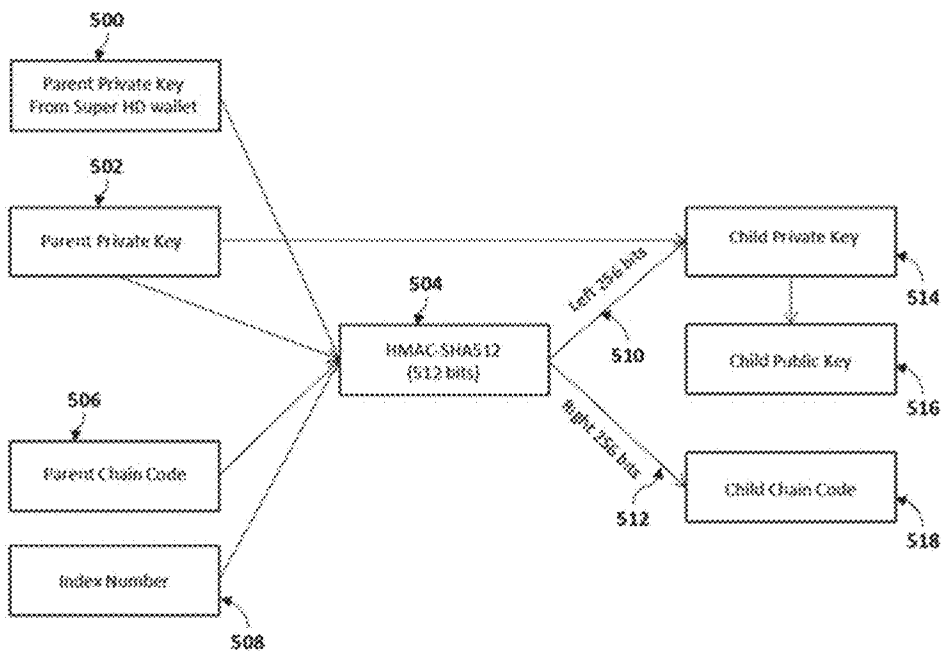

500
Parent Private Key From Super HD wallet
502
Parent Private Key
504
HMAC-SHA512 (512 bits)
506
Parent Chain Code
Index Number
508
Left 256 bits
510
Right 256 bits
512
Child Private Key
514
Child Public Key
516
Child Chain Code
518

FIG. 7


550
552
554
556
558
560
#Generate master key for Super HD Wallet
#Generate master key for Toughened HD Wallet-1
#Generate master key for Toughened HD Wallet-2
#Generate m/0H' hardened & toughened key for Toughened HD Wallet-1
#Generate m/0H' hardened & toughened key for Toughened HD Wallet-2

FIG. 8

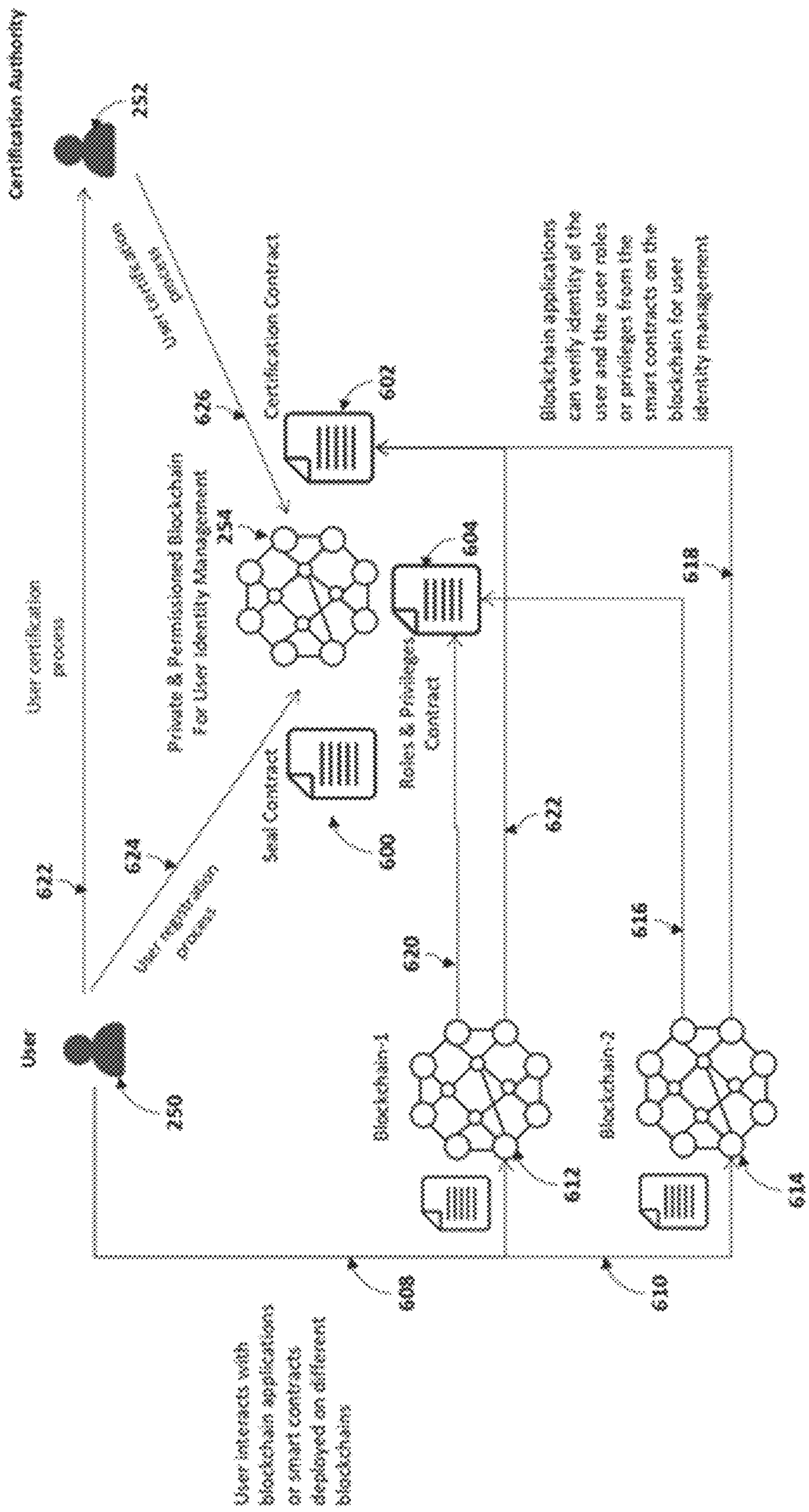

Certification Authority
252
User certification process
User certification process
626
Certification Contract
602
Blockchain applications can verify identity of the user and the user roles or privileges from the smart contracts on the blockchain for user identity management
Private & Permissioned Blockchain For User Identity Management
254
604
618
Roles & Privileges Contract
Seal Contract
600
622
632
624
User registration process
User
250
620
616
Blockchain-1
Blockchain-2
612
614
608
610
User interacts with blockchain applications or smart contracts deployed on different blockchains

FIG. 9

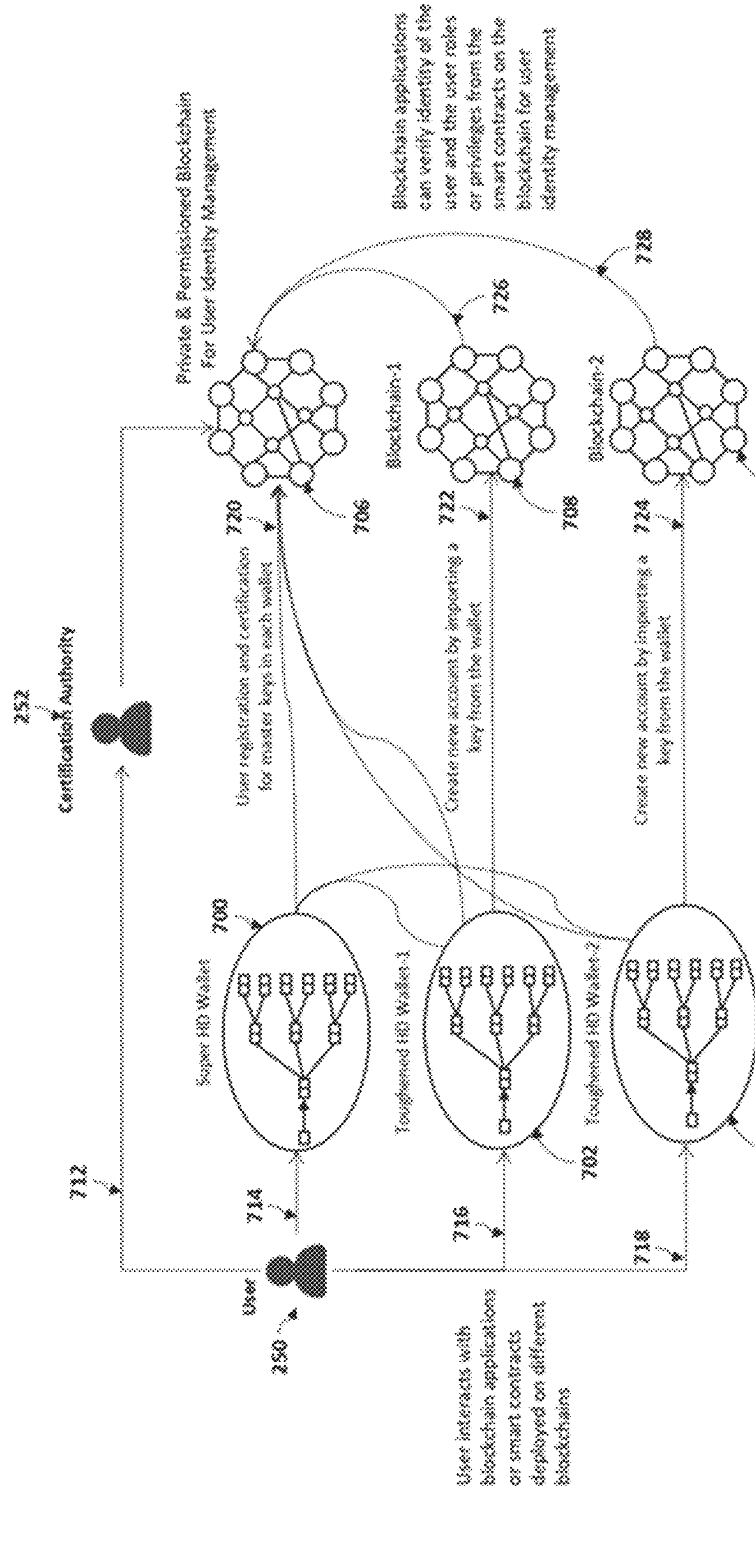
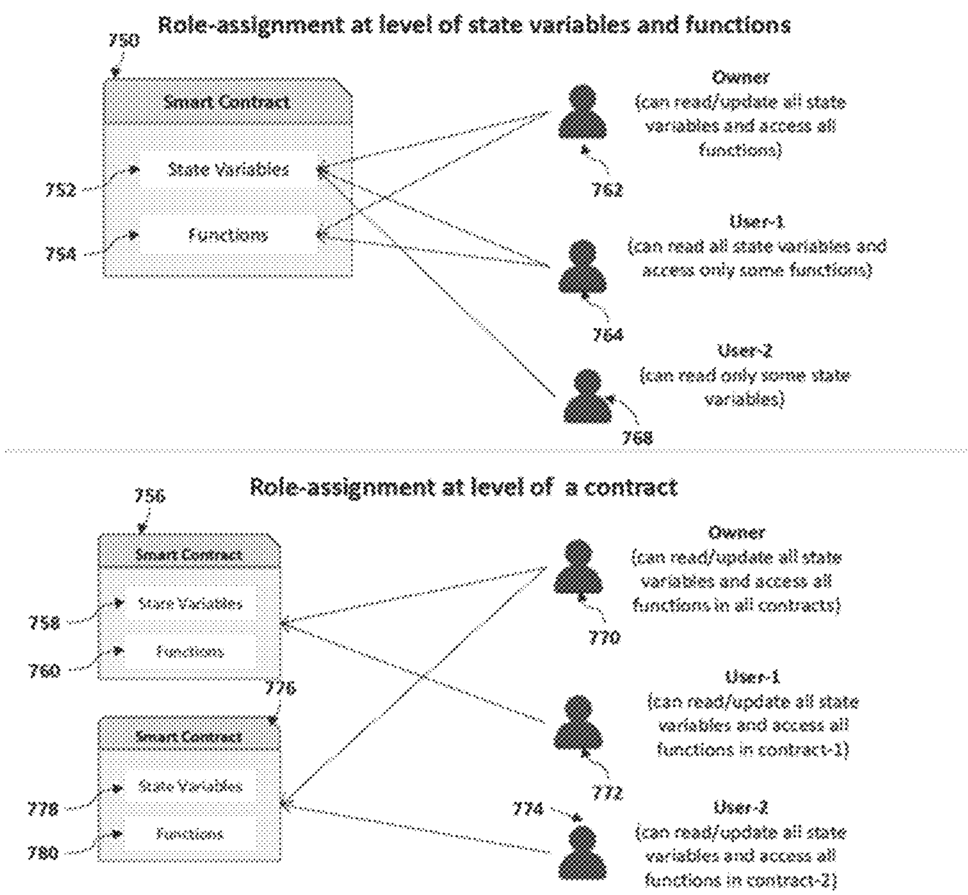

Private & Permissioned Blockchain
For User Identity Management
Blockchain applications can verify identity of the user and the user roles or privileges from the smart contracts on the blockchain for user identity management
728
726
Blockchain-1
Blockchain-2
706
708
710
720
722
724
User registration and certification for master key in each wallet
Create new account by importing a key from the wallet
Create new account by importing a key from the wallet
252
Certification Authority
Super HD Wallet
700
Toughened HD Wallet-1
702
Toughened HD Wallet-2
704
712
714
716
718
User
250
User interacts with blockchain applications or smart contracts deployed on different blockchains

FIG. 10



Role-assignment at level of state variables and functions
750
Smart Contract
State Variables
Functions
752
754
Owner
(can read/update all state variables and access all functions)
762
User-1
(can read all state variables and access only some functions)
764
User-2
(can read only some state variables)
768
Role-assignment at level of a contract
756
Smart Contract
State Variables
Functions
758
760
776
Smart Contract
State Variables
Functions
778
780
Owner
(can read/update all state variables and access all functions in all contracts)
770
User-1
(can read/update all state variables and access all functions in contract-1)
772
774
User-2
(can read/update all state variables and access all functions in contract-2)

FIG. 11

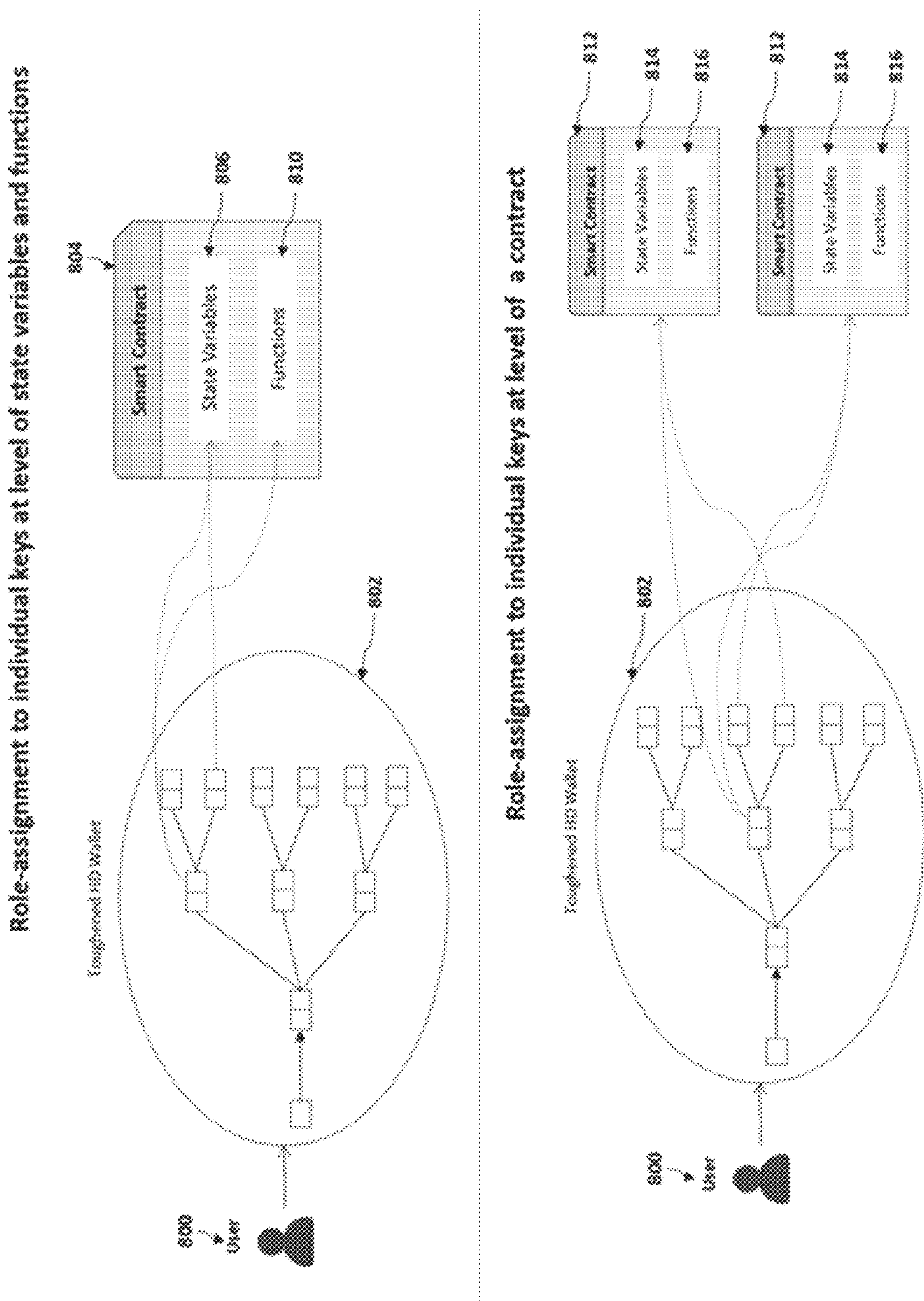

Role-assignment to individual keys at level of state variables and functions
804
Smart Contract
State Variables
Functions
806
810
802
Toughened HD Wallet
800
User
Role-assignment to individual keys at level of a contract
812
814
816
Smart Contract
State Variables
Functions
812
814
816
Smart Contract
State Variables
Functions
802
Toughened HD Wallet
800
User

FIG. 12

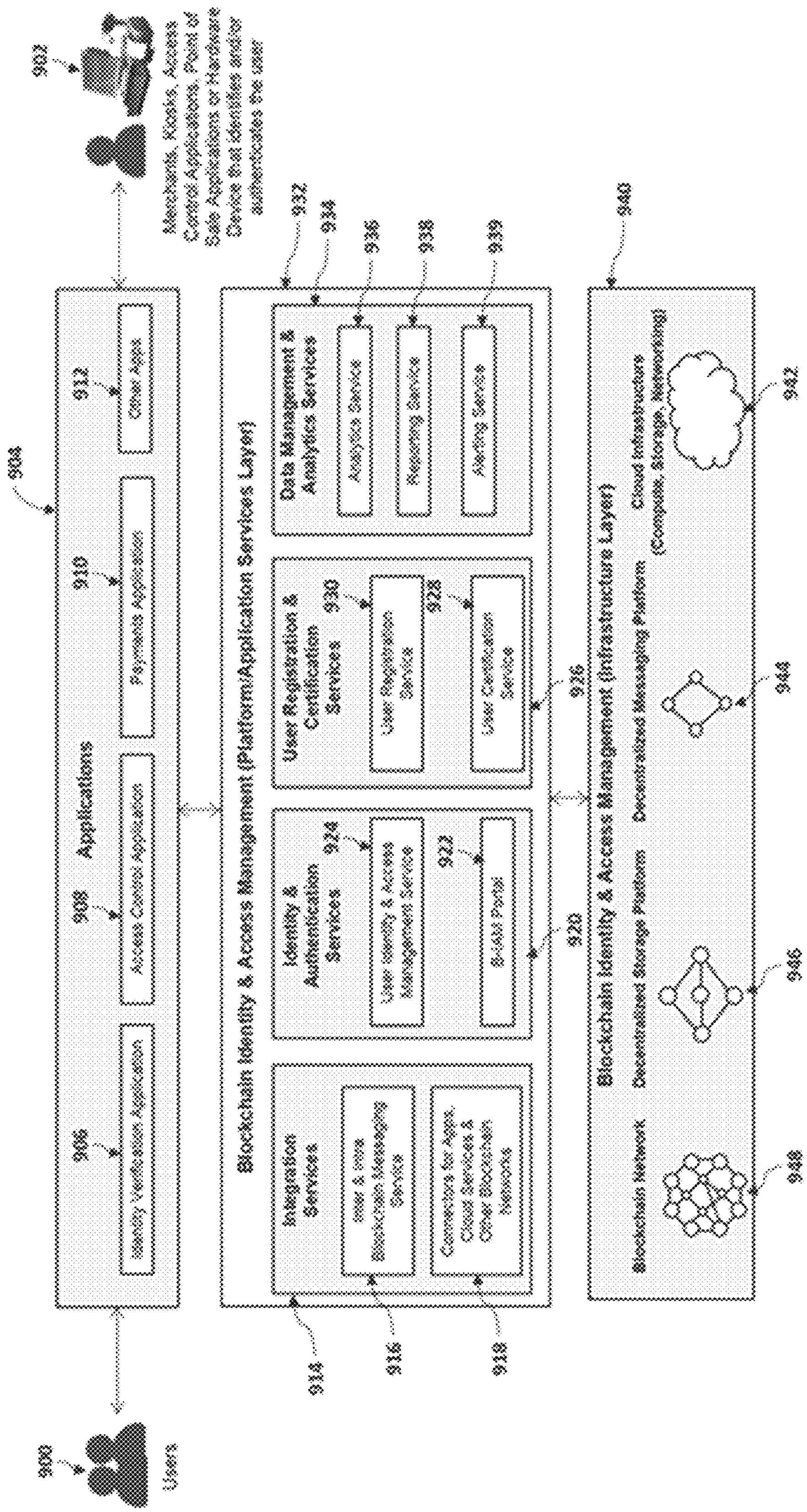

900
Users
904
Applications
906
Identity Verification Application
908
Access Control Application
910
Payments Application
912
Other Apps
902
Merchants, Kiosks, Access Control Applications, Point of Sale Applications or Hardware Device that identifies and/or authenticates the user
932
Blockchain Identity & Access Management (Platform/Application Services Layer)
914
Integration Services
916
Inter & Intra Blockchain Messaging Service
918
Connectors for Apps, Cloud Services & Other Blockchain Networks
920
Identity & Authentication Services
924
User Identity & Access Management Service
922
BIAM Portal
926
User Registration & Certification Services
930
User Registration Service
928
User Certification Service
934
Data Management & Analytics Services
936
Analytics Service
938
Reporting Service
939
Alerting Service
940
Blockchain Identity & Access Management (Infrastructure Layer)
Blockchain Network
948
Decentralized Storage Platform
946
Decentralized Messaging Platform
944
Cloud Infrastructure (Compute, Storage, Networking)
942

FIG. 13

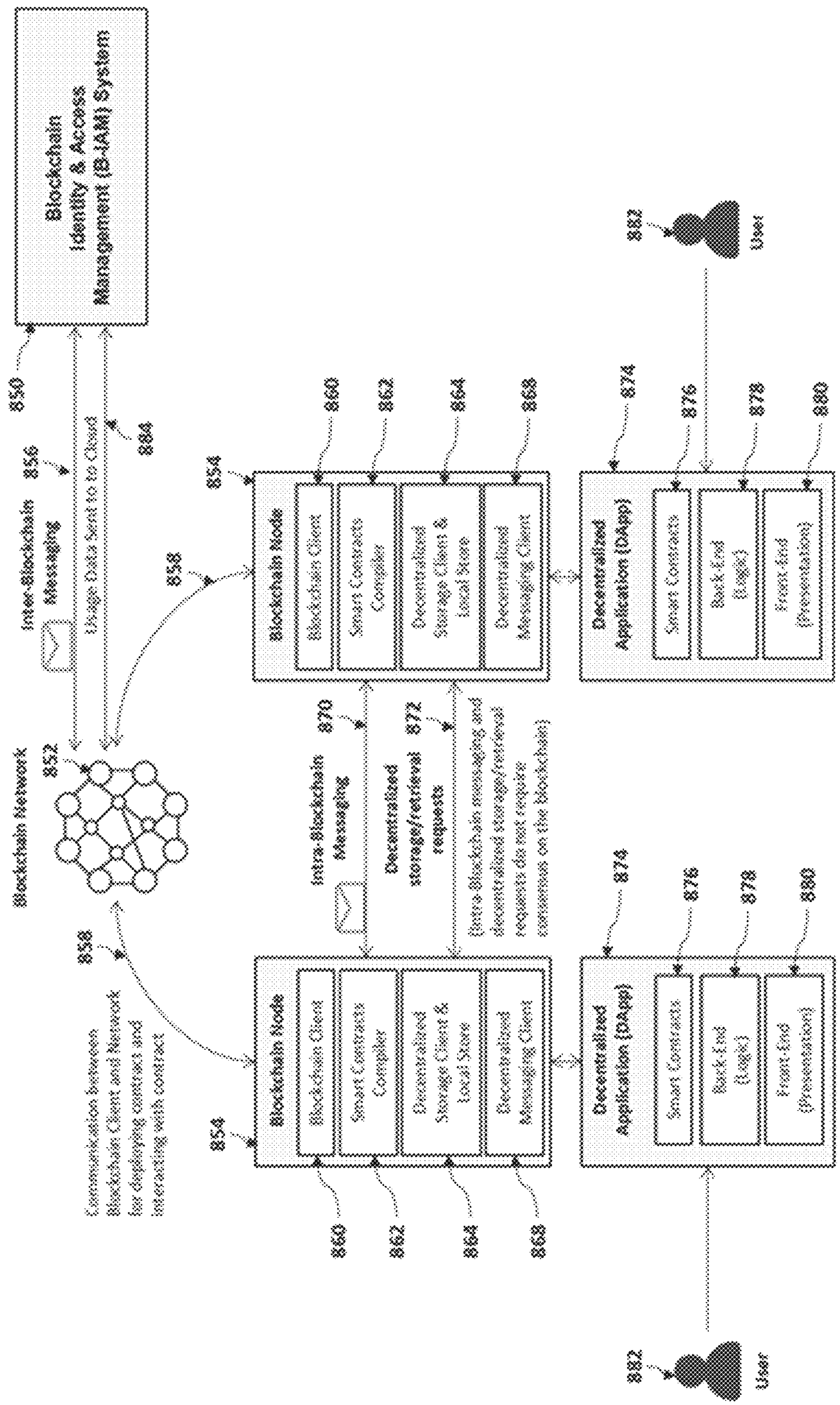

Blockchain Identity & Access Management (B-IAM) System
850
Inter-Blockchain Messaging
856
Usage Data Sent to Cloud
884
858
Blockchain Network
852
854
Blockchain Node
Blockchain Client
Smart Contracts Compiler
Decentralized Storage Client & Local Store
Decentralized Messaging Client
860
862
864
868
874
Decentralized Application (DApp)
Smart Contracts
Back-End (Logic)
Front-End (Presentation)
876
878
880
882
User
Intra-Blockchain Messaging
870
Decentralized storage/retrieval requests
872
(Intra-Blockchain messaging and decentralized storage/retrieval requests do not require consensus on the blockchain)
Communication between Blockchain Client and Network for deploying contracts and interacting with contract
863

FIG. 14

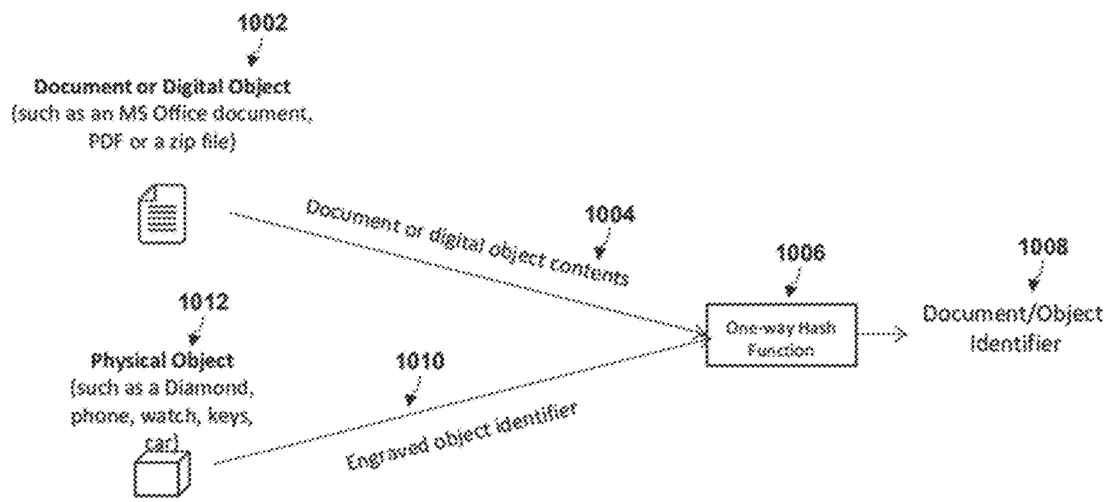

1002
Document or Digital Object
(such as an MS Office document, PDF or a zip file)
Document or digital object contents
1004
1006
One-way Hash Function
1008
Document/Object Identifier
1012
Physical Object
(such as a Diamond, phone, watch, keys, car)
1010
Engraved object identifier

FIG. 15

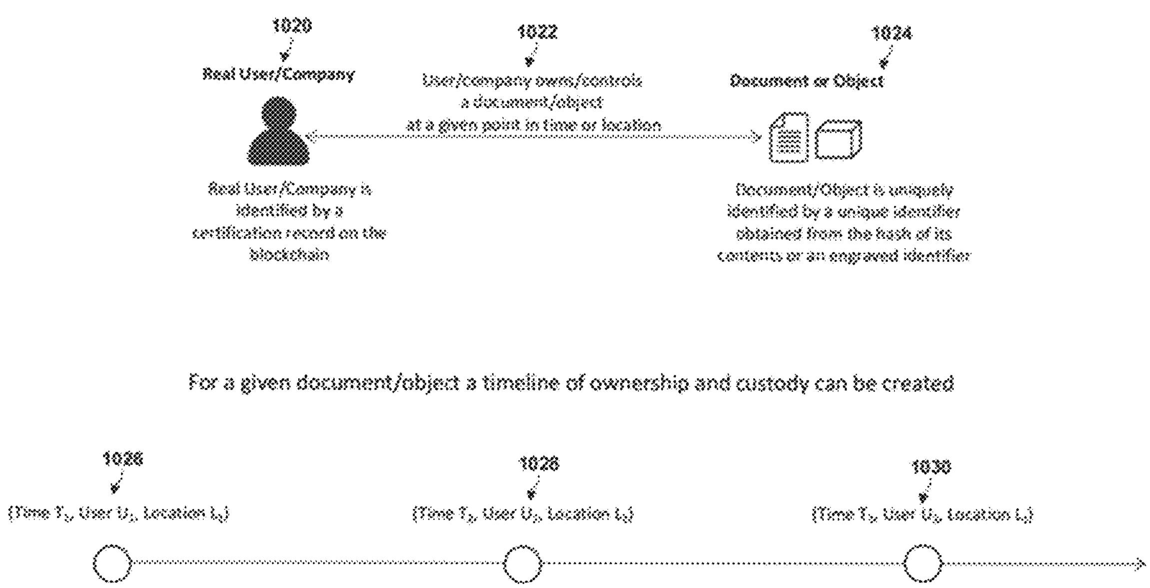
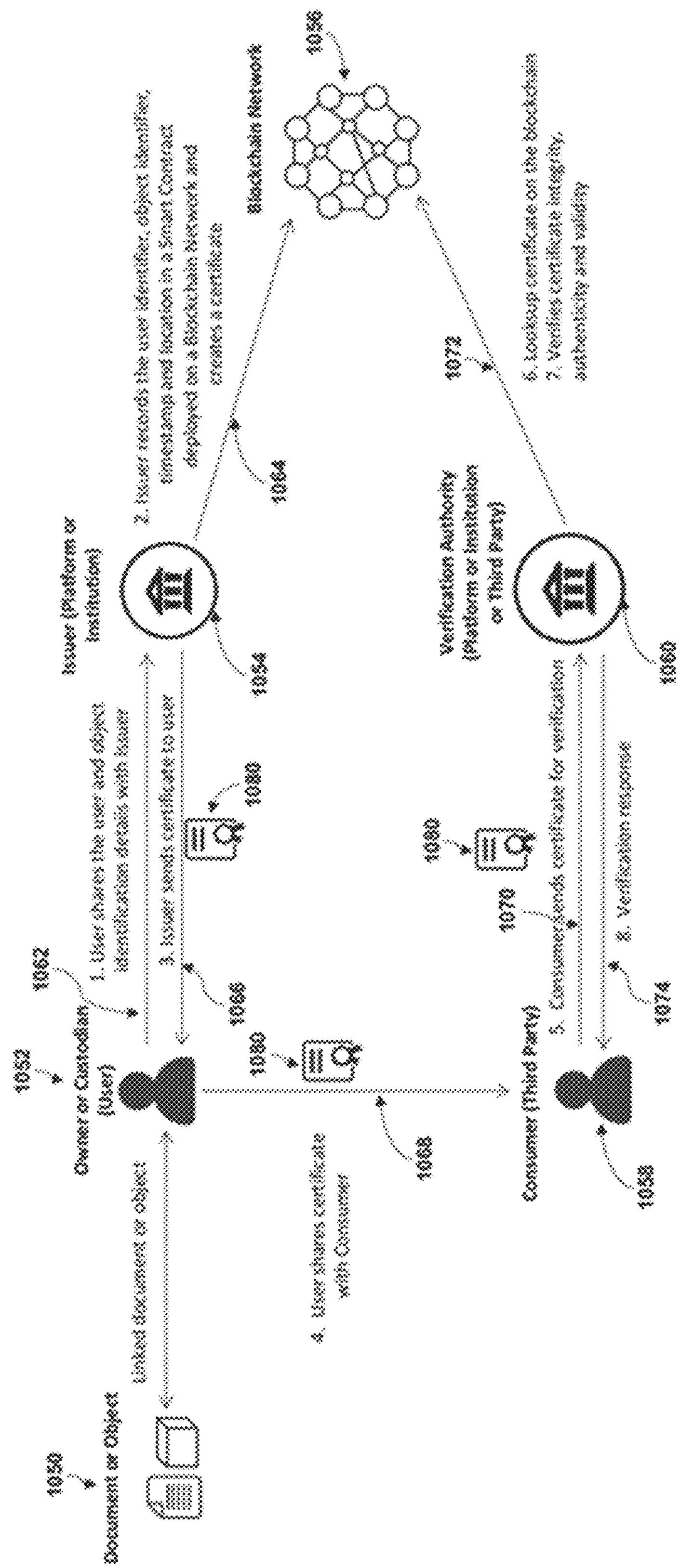

1020
Real User/Company
1022
User/company owns/controls a document/object at a given point in time or location
1024
Document or Object
Real User/Company is identified by a certification record on the blockchain
Document/Object is uniquely identified by a unique identifier obtained from the hash of its contents or an engraved identifier
For a given document/object a timeline of ownership and custody can be created
1026
{Time T_1, User U_1, Location L_1}
1028
{Time T_2, User U_2, Location L_2}
1030
{Time T_3, User U_3, Location L_3}

FIG. 16



1050
Document or Object
Linked document or object
1052
Owner or Custodian (User)
1054
Issuer (Platform or Institution)
1056
Blockchain Network
1058
Consumer (Third Party)
1060
Verification Authority (Platform or Institution or Third Party)
1062
1. User shares the user and object identification details with Issuer
1064
2. Issuer records the user identifier, object identifier, timestamp and location in a Smart Contract deployed on a Blockchain Network and creates a certificate
1066
3. Issuer sends certificate to user
1068
4. User shares certificate with Consumer
1070
5. Consumer sends certificate for verification
1072
6. Lookup certificate on the blockchain
7. Verifies certificate integrity, authenticity and validity
1074
8. Verification response
1080
1080
1080

FIG. 17

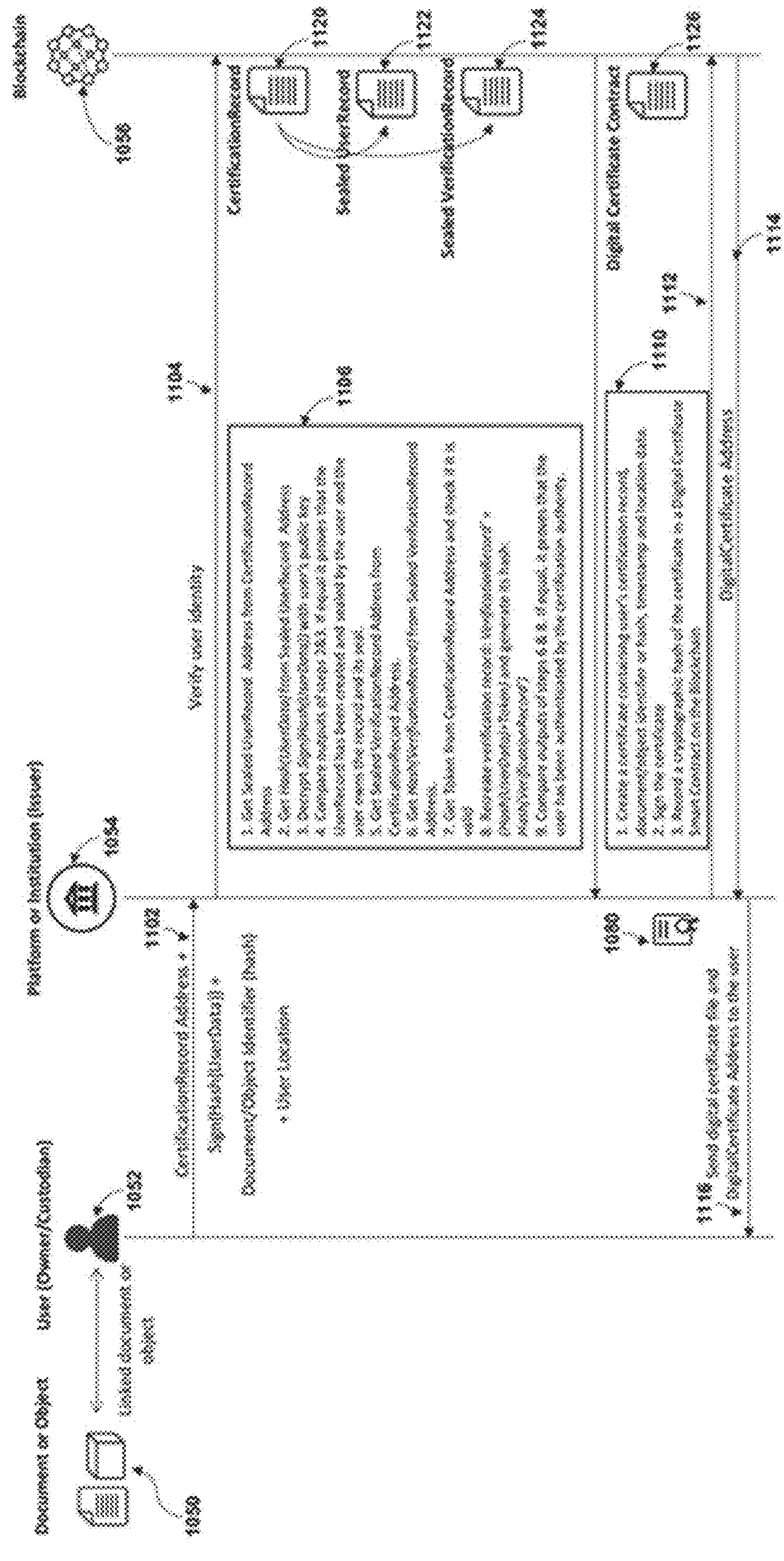

Document or Object
User (Owner/Custodian)
Linked document or object
Platform or Institution (Issuer)
Blockchain
1050
1052
1054
1056
1102
1104
1106
1110
1112
1114
1116
1120
1122
1124
1126
1060
Verify user identity
Certification Record
Sealed User Record
Sealed Verification Record
Digital Certificate Contract
Digital Certificate Address
+ User Location
Send digital certificate file and DigitalCertificate Address to the user

FIG. 18

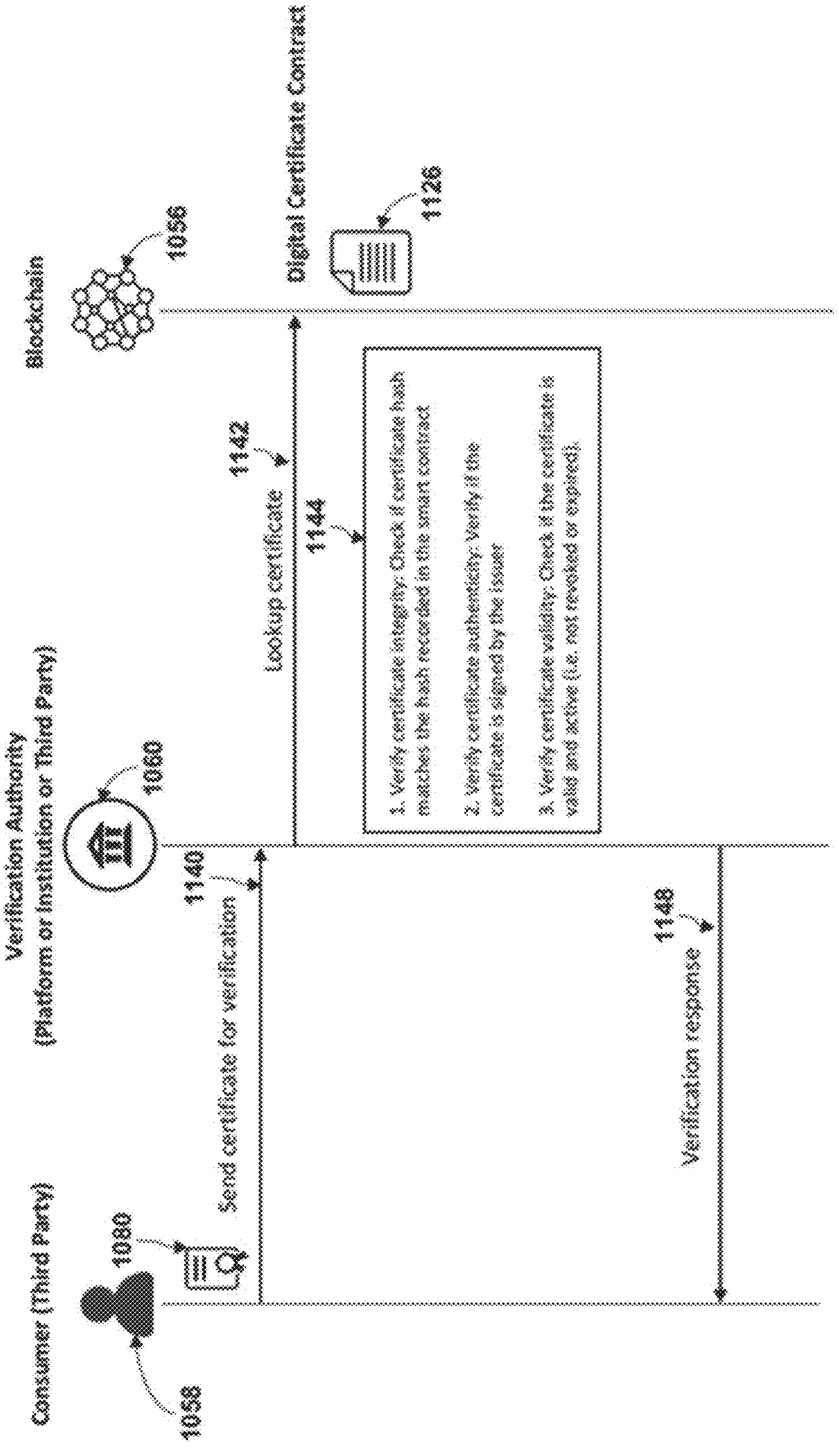

Consumer (Third Party)
1058
1080
Verification Authority
(Platform or Institution or Third Party)
1060
Blockchain
1056
Digital Certificate Contract
1126
Send certificate for verification
1140
Lookup certificate
1142
1144
1. Verify certificate integrity: Check if certificate hash matches the hash recorded in the smart contract
2. Verify certificate authenticity: Verify if the certificate is signed by the issuer
3. Verify certificate validity: Check if the certificate is valid and active (i.e. not revoked or expired).
Verification response
1148

FIG. 19

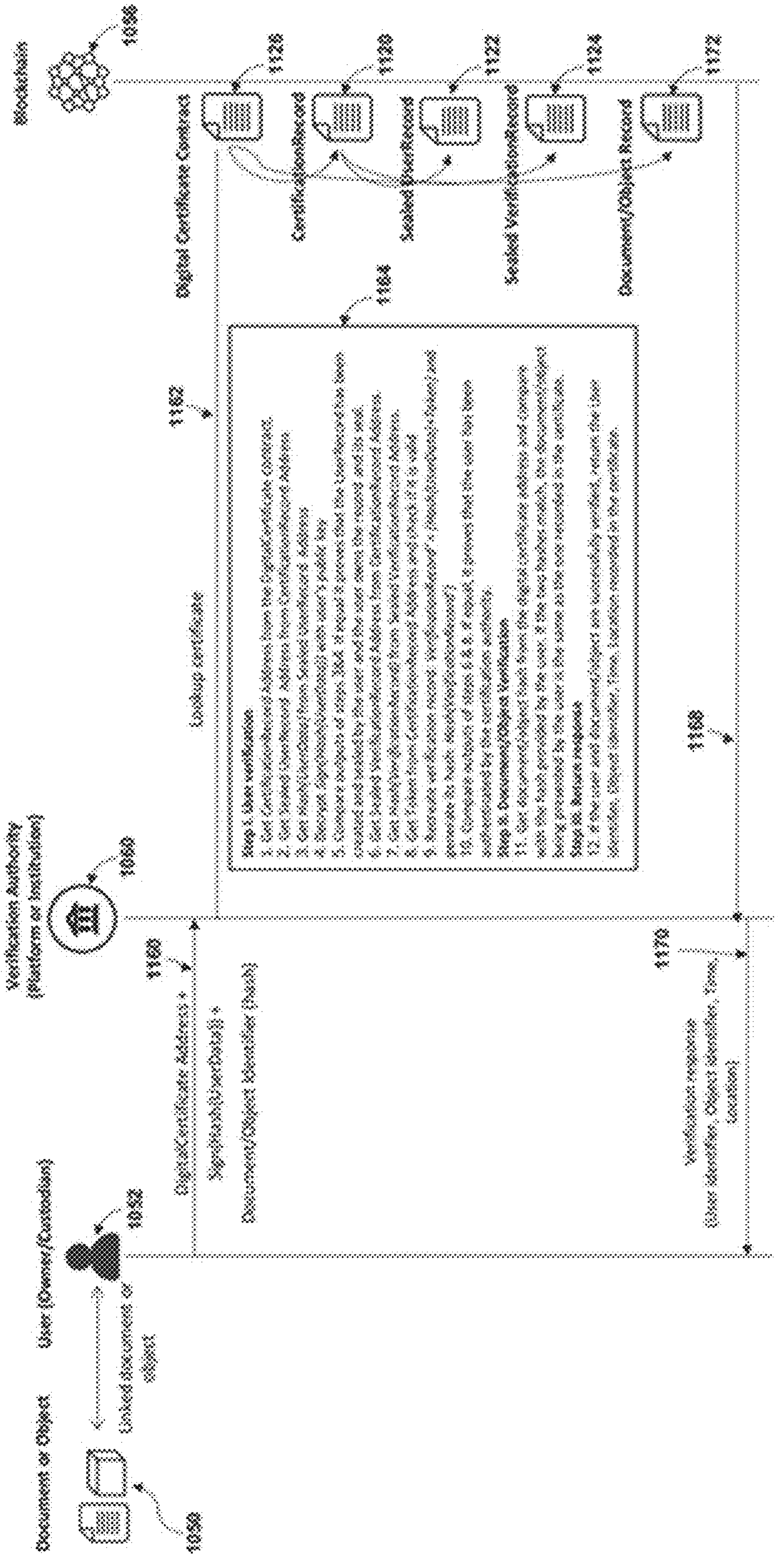


FIG. 20

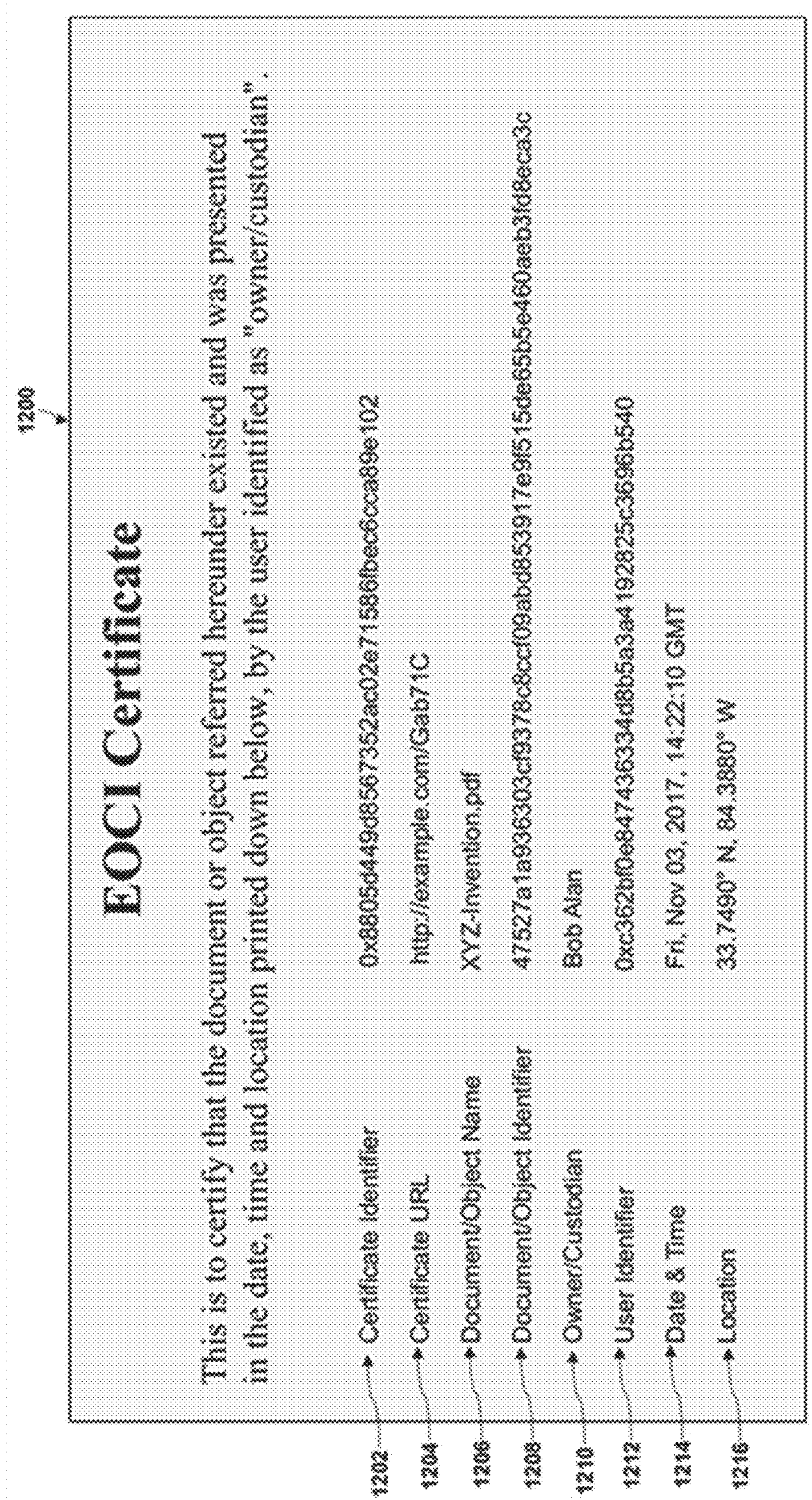
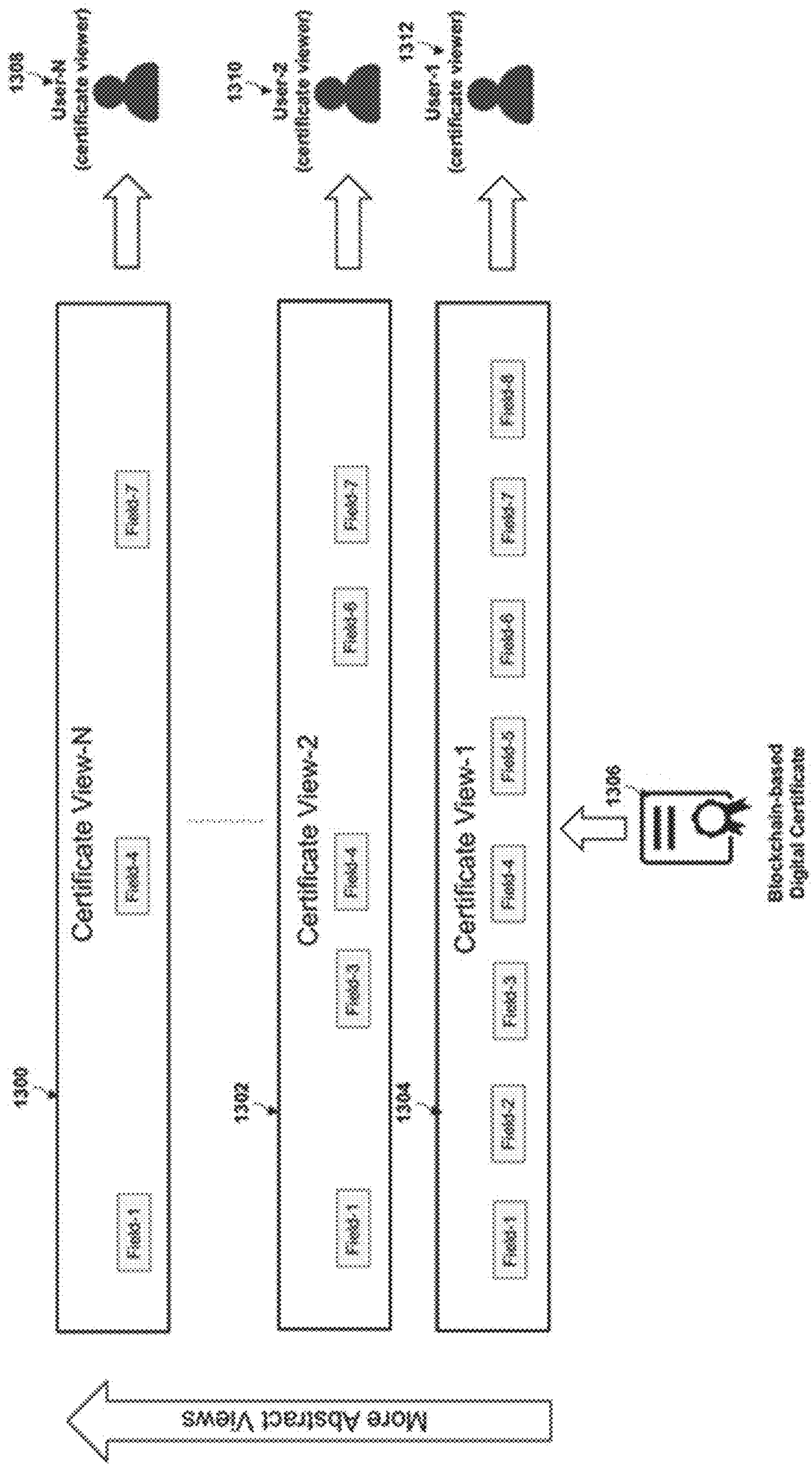
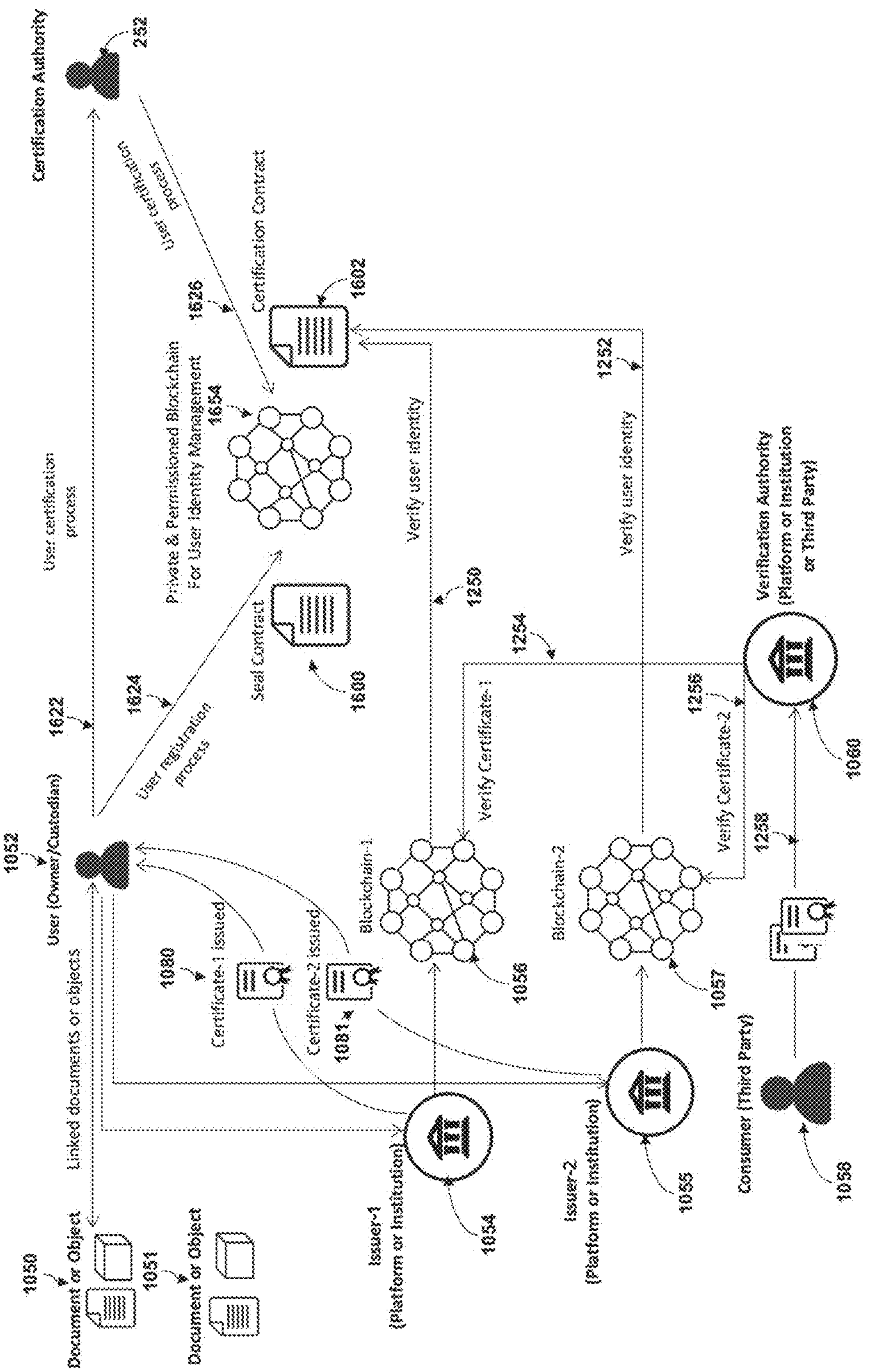

1200
EOCI Certificate
This is to certify that the document or object referred hereunder existed and was presented in the date, time and location printed down below, by the user identified as "owner/custodian".
1202 Certificate Identifier 0x8805d449d8567352ac02e71586bec6cca89e102
1204 Certificate URL http://example.com/Gab71C
1206 Document/Object Name XYZ-Invention.pdf
1208 Document/Object Identifier 47527a1a936303cf9378c8ccf09abd853917e9f515de65b5e460aeb3fd8eca3c
1210 Owner/Custodian Bob Alan
1212 User Identifier 0xc362bf0e8474363334d8b5a3a4192825c3696b540
1214 Date & Time Fri, Nov 03, 2017, 14:22:10 GMT
1216 Location 33.7490° N, 84.3880° W

FIG. 21



1308
User-N
(certificate viewer)
1310
User-2
(certificate viewer)
1312
User-1
(certificate viewer)
Certificate View-N
Certificate View-2
Certificate View-1
1300
1302
1304
Field-1
Field-2
Field-3
Field-4
Field-5
Field-6
Field-7
Field-8
1306
Blockchain-based
Digital Certificate
More Abstract Views

FIG. 22



Certification Authority
252
User certification process
Certification Contract
1602
1626
Private & Permissioned Blockchain For User Identity Management
1654
User certification process
Verify user identity
1252
Verify user identity
1250
Seal Contract
1600
1624
1622
User registration process
1052
User (Owner/Custodian)
1254
Verify Certificate-1
Verification Authority (Platform or Institution or Third Party)
1256
Verify Certificate-2
1060
Blockchain-1
Blockchain-2
1258
1080
Certificate-1 issued
Certificate-2 issued
1081
1056
1057
Linked documents or objects
1050
Document or Object
1051
Document or Object
Issuer-1 (Platform or Institution)
1054
Issuer-2 (Platform or Institution)
1055
Consumer (Third Party)
1058

FIG. 23

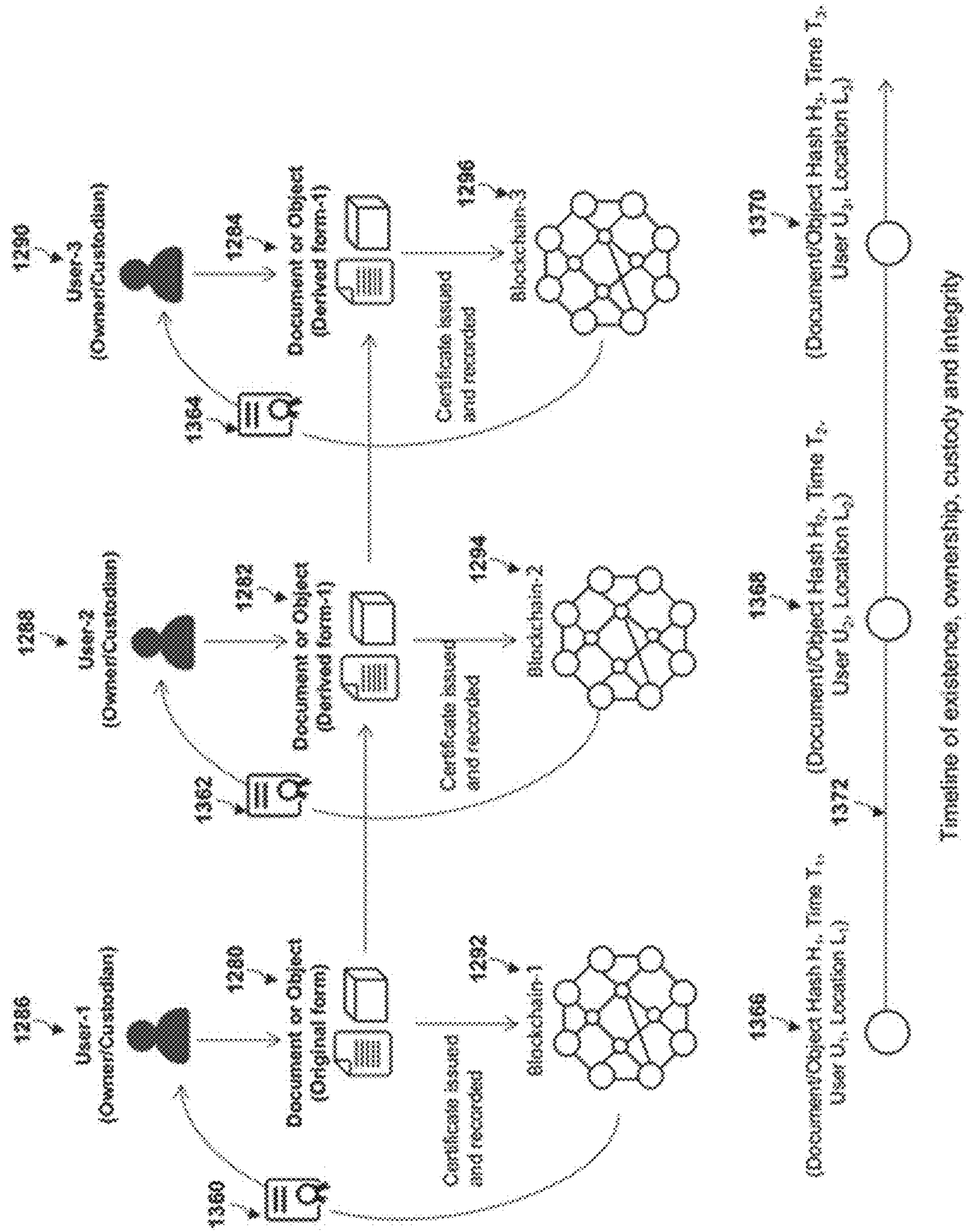

1286
User-1
(Owner/Custodian)
1280
Document or Object
(Original form)
1292
Blockchain-1
Certificate issued
and recorded
1360
1288
User-2
(Owner/Custodian)
1282
Document or Object
(Derived form-1)
1294
Blockchain-2
Certificate issued
and recorded
1362
1290
User-3
(Owner/Custodian)
1284
Document or Object
(Derived form-1)
1296
Blockchain-3
Certificate issued
and recorded
1364
1366
(Document/Object Hash H_1, Time T_1,
User U_1, Location L_1)
1372
1368
(Document/Object Hash H_2, Time T_2,
User U_2, Location L_2)
1370
(Document/Object Hash H_3, Time T_3,
User U_3, Location L_3)
Timeline of existence, ownership, custody and integrity

FIG. 24

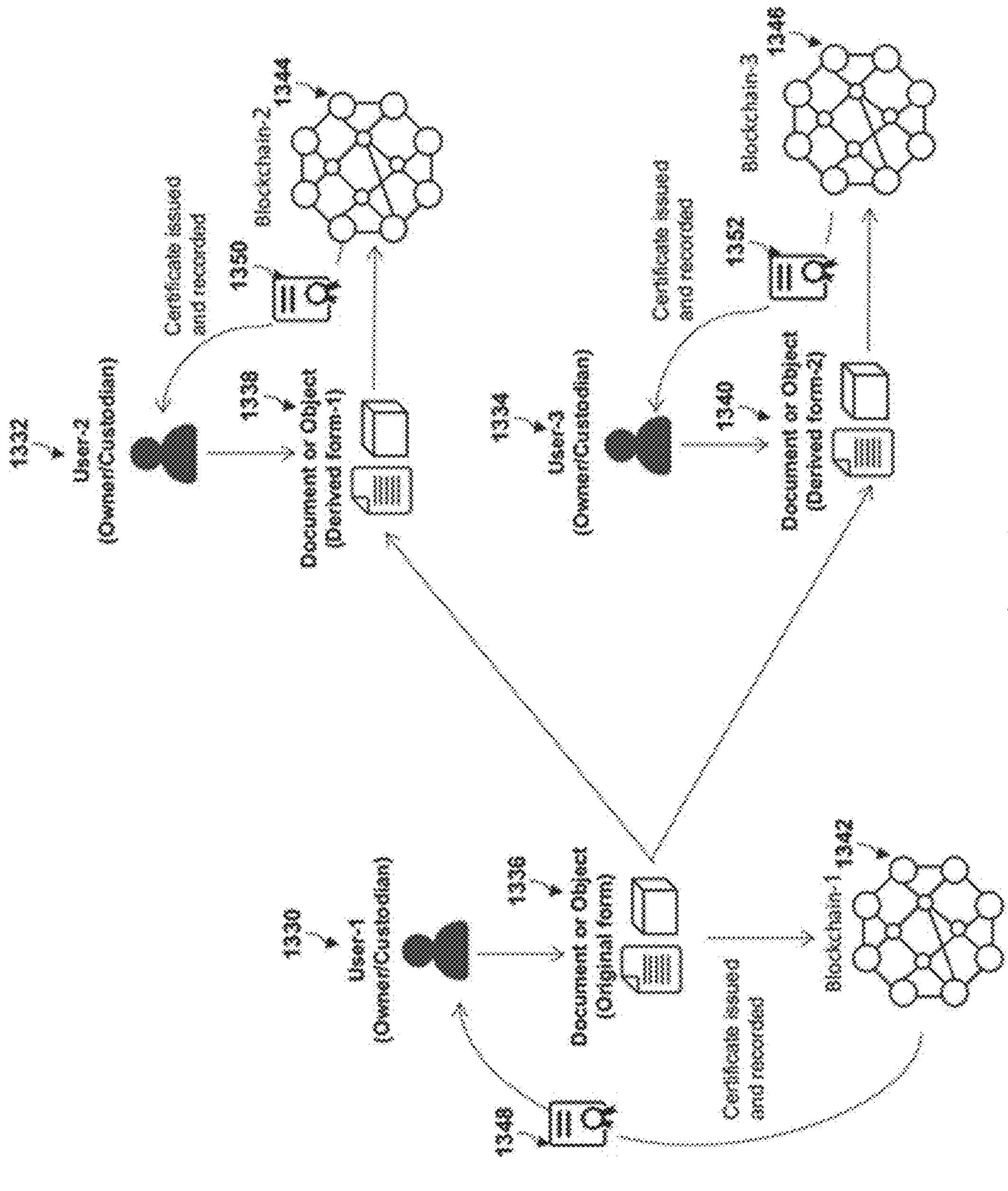

1330
User-1
(Owner/Custodian)
1336
Document or Object
(Original form)
1342
Blockchain-1
1348
Certificate issued
and recorded
1332
User-2
(Owner/Custodian)
1338
Document or Object
(Derived form-1)
1344
Blockchain-2
1350
Certificate issued
and recorded
1334
User-3
(Owner/Custodian)
1340
Document or Object
(Derived form-2)
1346
Blockchain-3
1352
Certificate issued
and recorded

FIG. 25

METHOD AND SYSTEM FOR BLOCKCHAIN-BASED COMBINED IDENTITY, OWNERSHIP, INTEGRITY AND CUSTODY MANAGEMENT

RELATED APPLICATIONS

This application is a continuation of and claims the benefit under 35 U.S.C. § 120 of U.S. patent application Ser. No. 16/032,480 titled Method and System for Blockchain-Based Combined Identity, Ownership, Integrity, and Custody Management and filed on Jul. 11, 2018, which in turn claims priority to U.S. patent application Ser. No. 15/863,128 titled Method and System for Blockchain-Based Combined Identity, Ownership, Integrity, and Custody Management and filed on Jan. 5, 2018, which in turn claims benefit under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application Ser. No. 62/479,966 titled Method and System for Identity and Access Management for Blockchain Interoperability and filed on Mar. 31, 2017, and U.S. Provisional Patent Application Ser. No. 62/582,422 titled Method And System For Blockchain-based Combined Identity, Ownership, Integrity And Custody Management and filed on Nov. 7, 2017, the entire contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to blockchain-based combined identity, ownership, integrity and custody management.

BACKGROUND

Blockchain is a distributed and public ledger which maintains records of all the transactions. A blockchain network is a truly peer-to-peer network and it does not require a trusted central authority or intermediaries to authenticate or to settle the transactions or to control the network infrastructure. Users can interact and transact with the blockchain networks through Externally Owned Account (EOAs), which are owned and controlled by the users. Each EOA has a balance (in certain units of a Cryptocurrency associated with the Blockchain network) associated with it. EOAs do not have any associated code. All transactions on a blockchain network are initiated by EOAs. These accounts can send transactions to other EOAs or contract accounts. Another type of accounts support by second generation programmable Blockchain platforms are the Contract Accounts. A Contract Account is created and owned by an EOA and is controlled by the associated contract code which is stored with the account. The contract code execution is triggered by transactions sent by EOAs or messages sent by other contracts.

Blockchain networks can either be public or private. Public blockchain networks are free and open to all and any user can create an account and participate in the consensus mechanism on a public blockchain and view all the transactions on the network. Private blockchain networks are usually controlled and operated by a single organization and the transactions can be viewed only by the users within the organization. Public blockchain networks are usually unpermissioned or permissionless, as any node can participate in consensus process. Some public blockchain networks adopt a permissioned model where the consensus process is controlled by a pre-selected set of nodes. Private blockchain networks usually adopt the permissioned model. While

public blockchain networks can be considered as fully decentralized, private blockchain networks are partially decentralized.

Organizations can have multiple private blockchain networks where each network is dedicated to a specific use case or department or business vertical. The blockchain networks within an organization may be created either using the same blockchain platform or technology or with different platforms or technologies.

On each blockchain network, a user can create multiple Externally Owned Accounts (EOAs). Each Externally Owned Account (EOA) has a public-private keypair associated with it. The account address is derived from the public key. When a new EOA is created, a keyfile is created which has the public and private keys associated with the account. The private key is encrypted with the password which is provided while creating the account. For sending transactions to other accounts, the private key and the account password are required.

Existing Blockchain platforms lack identity management beyond the blockchain accounts and there is no way to know if two blockchain accounts belong to the same person. Blockchain applications can be prone to Sybil attacks where the attacker can create a large number of pseudonymous identities and then use them to gain a large influence on the network. In existing Blockchain platforms, there is no way to securely link a blockchain account to a real-user. Prior art linking blockchain accounts to real users is based on know your customer (KYC) processes that require the user to provide KYC documents such as a government issued identity card (such as passport or driving license). The KYC processes require manual verification by the platform or application team. When using multiple private and/or permissioned blockchain networks within a single organization, there is no way for a user to work on multiple blockchain networks while maintaining the same identity. For multiple blockchain networks within an organization or different applications deployed on the same blockchain network, existing solutions require the KYC process to be completed separately either for each blockchain network or for each application.

Existing Proof-of-Existence approaches based on the blockchain technology allow generating ownership certificates for digital objects. An ownership certificate includes an object identifier (such as a cryptographic hash generated from the object contents), owner name, time stamp of generation of the certificate and other related information. In Proof-of-Existence platforms, there is no way to securely link the ownership of a digital object to a verified user, prevent user from using pseudonymous identities or determine a timeline of ownership and custody of digital objects.

This background information is provided to reveal information believed by the applicant to be of possible relevance to the present invention. No admission is necessarily intended, nor should be construed, that any of the preceding information constitutes prior art against the present invention.

SUMMARY OF THE INVENTION

With the above in mind, embodiments of the present invention are related to a method of issuing blockchain-based digital certificates comprising receiving from a user hashed user identification information and object information recording to a digital certificate smart contract deployed at a digital certificate smart contract address on a blockchain network the hashed user identification information and object information and a timestamp of when the hashed user identification information and the object information were received, defined as a received timestamp, signing the digital certificate smart contract with an issuer signature, and performing a user identity verification process to confirm a user identity. Upon confirming the user identity, the method may further comprise generating a combination certificate configured to be shared by the user to verify the user's ownership of an object associated with the object information and sending the combination certificate to the user.

In some embodiments, the object information may be derived from a digital object comprising content; and wherein the object information comprises a unique identifier generated by applying a cryptographic hash function to the content of the digital object. The object information may alternatively be derived from a physical object comprising an object identifier; and wherein the object information comprise a unique identifier generated by applying a cryptographic hash to the object identifier of the physical object.

In some embodiments the method may further comprise receiving an combination certificate from a consumer, defining a received combination certificate, performing an combination certificate verification process on the received ownership certification to verify the received combination certificate and upon verifying the received combination certificate, sending a confirmation verification response to the consumer. The method may further comprise generating a combination certificate hash value by applying a hash function to the received combination certificate and recording the combination certificate hash value to the digital certificate smart contract. The combination certificate verification process may comprise identifying a signature of the received combination certificate, obtaining a received digital certificate smart contract address from the received combination certificate, generating a query hash value by applying a hash function to the received combination certificate, looking up the combination certificate on the digital certificate smart contract at the digital certificate smart contract address, verifying the query hash value matches an combination certificate hash value comprised by the digital certificate smart contract, verifying the signature of the combination certificate matches the issuer signature of the digital certificate smart contract, and verifying the combination certificate is valid and active.

In some embodiments, the method may further comprise receiving from the user a digital certificate smart contract address, hashed user identification information signed by a private key of the user, and hashed object information, obtaining a user certification record address from a digital certificate smart contract at the digital certificate smart contract address, obtaining a sealed user record address, a sealed verification record address, and a token from a user certification record at the user certification record address, retrieving hashed user identification information, defined as retrieved user identification information, from a sealed user record at the sealed user record address, and decrypting the received user identification information using the user's public key, defining decrypted user identification information. The decrypted user identification information with the retrieved user identification information may be compared. The method may further comprise retrieving a hashed verification record from a sealed verification record at the sealed verification record address, determining if the token from the user certification record address is valid, generating a generated verification record comprising the retrieved user identification information and the token; generating a hashed generated verification record by applying a hash function to the generated verification record, and comparing the hashed generated verification record to the hashed verification record. The method may further comprise retrieving object information, defining retrieved object information, from the digital certificate at the digital certificate address, comparing the retrieved object information with the hashed object information, and retrieving from the digital certificate smart contract a timestamp, defining a retrieved timestamp. Upon determining the decrypted user identification information with the retrieved user identification information are at least a partial match, the hashed generated verification record to the hashed verification record are at least a partial match, and the retrieved object information and the hashed object information are at least a partial match, the method may further comprise sending to the user the retrieved user identification information, the retrieved object information, and the retrieved timestamp.

In some embodiments, performing the user validation process may comprise receiving from the user a user certification record address, hashed user identification information that has been signed with a private key of the user defined as received user identification information, hashed object information defined as received object information, and a user public key, obtaining each of a sealed user record address, a sealed verification record address, and a token from a user certification record address at the user certification record address, retrieving hashed user identification information from a sealed user record at the sealed user record address, defining retrieved user identification information, decrypting the received user identification information using the user public key, defining decrypted user identification information, and comparing the decrypted user identification information with the retrieved user identification information. Performing the user validation process may further comprise retrieving a hashed verification record from a sealed verification record at the sealed verification record address, defining a retrieved verification record, and determining if the token from the user certification record address is valid. Upon determining the token from the user certification record address is valid, performing the user validation process may further comprise generating a generated verification record comprising the retrieved user identification information and the token, generating a hashed verification record by applying a hash function to the generated verification record, comparing the hashed verification record with the retrieved verification record, and confirming the user identity by determining the decrypted user identification information and the retrieved user identification information are at least a partial match and the hashed verification record and the retrieved verification record are at least a partial match.

In some embodiments, generating the combination certificate may comprise generating a combination certificate comprising the user's certification record address, the received object information, and the received timestamp, generating a combination certificate hash value from a hash function including the combination certificate as an input, encrypting the combination certificate hash value with an issuer private key, defining an issuer signature, signing the combination certificate with the issuer signature, defining a signed combination certificate, and recording the signed combination certificate to the digital certificate smart contract.

In some embodiments, the method may further comprise receiving hashed second user identification information associated with a second user and a derivative of the object information, defining a derivative object information, recording to a second digital certificate smart contract deployed at a second digital certificate smart contract address on a second blockchain network the hashed second user identification information and the derivative object information and a timestamp of when the hashed second user identification information and the derivative object information were received, defined as a received timestamp, signing the second digital certificate smart contract with a second issuer signature, generating a second combination certificate configured to be shared by the second user to verify the second user's ownership of a derivative object associated with the derivative object information, and sending the second combination certificate to the second user. Furthermore, the object information may be derived from a digital object comprising content, and the derivative object may be a digital object comprising a subset of the content of the digital object from which the digital object is derived. The derivative object information may comprise a unique identifier generated by applying a cryptographic hash function to the derivative object.

In some embodiments, the method may further comprise receiving hashed third user identification information associated with a third user and the derivative object information, recording to a third digital certificate smart contract deployed at a third digital certificate smart contract address on a third blockchain network the hashed third user identification information and the derivative object information and a timestamp of when the hashed third user identification information and the derivative object information were received, defined as a received timestamp, signing the third digital certificate smart contract with a third issuer signature, generating a third combination certificate configured to be shared by the third user to verify the third user's ownership of a derivative object associated with the derivative object information, sending the third combination certificate to the third user, and recording to the second digital certificate smart contract an indication that the second digital certificate smart contract is expired.

In some embodiments, the method may further comprise receiving hashed third user identification information associated with a third user and a second derivative of the object information, defining a second derivative object information, recording to a third digital certificate smart contract deployed at a third digital certificate smart contract address on a third blockchain network the hashed third user identification information and the second derivative object information and a timestamp of when the hashed third user identification information and the second derivative object information were received, defined as a received timestamp, signing the third digital certificate smart contract with a third issuer signature, generating a third combination certificate configured to be shared by the third user to verify the third user's ownership of a derivative object associated with the second derivative object information, and sending the third combination certificate to the third user. The second derivative object information may exist concurrently with the derivative object information.

The method may further comprise generating a secondary combination certificate configured to be shared by the user to verify the user's ownership of a subset of information object associated with the object information and sending the secondary combination certificate to a second user. Furthermore, the method may additionally comprise receiving a secondary combination certificate from a consumer, defining a received combination certificate, and performing a combination certificate verification process on the received ownership certification to verify the received combination certificate. Upon verifying the received combination certificate, the message may further comprise sending a confirmation verification response to the consumer and sending a subset of information comprised by the object information to the consumer.

In some embodiments the method may further comprising recording to the digital certificate smart contract a location of the user when the user identification information and the object information were received. In some embodiments, the blockchain network may support at least one decentralized consensus protocols of proof-of-work proof-of-stake, proof-of-activity, proof-of-burn, proof-of-capacity, and proof-of-elapsed time.

Additionally, embodiments of the invention may be directed to a method of issuing blockchain-based digital certificates comprising receiving from a user a user certification record address, hashed user identification information that has been signed with a private key of the user defined as received user identification information, hashed object information defined as received object information, and a user public key, recording to a digital certificate smart contract deployed at a digital certificate smart contract address on a blockchain network the received user identification information and the received object information and a timestamp of when the received user identification information and the received object information were received, defined as a received timestamp, and signing the digital certificate smart contract with an issuer signature. The method may further comprise performing a user validation process comprising obtaining each of a sealed user record address, a sealed verification record address, and a token from a user certification record address at the user certification record address, retrieving hashed user identification information from a sealed user record at the sealed user record address, defining retrieved user identification information, decrypting the received user identification information using the user public key, defining decrypted user identification information, comparing the decrypted user identification information with the retrieved user identification information, retrieving a hashed verification record from a sealed verification record at the sealed verification record address, defining a retrieved verification record, and determining if the token from the user certification record address is valid. Upon determining the token from the user certification record address is valid, the user validation process may further comprise generating a generated verification record comprising the retrieved user identification information and the token, generating a hashed verification record by applying a hash function to the generated verification record, comparing the hashed verification record with the retrieved verification record and confirming a user identity by determining the decrypted user identification information and the retrieved user identification information are at least a partial match and the hashed verification record and the retrieved verification record are at least a partial match. Upon confirming the user identity, the method may further comprise generating a combination certificate comprising the user's certification record address, the object information, and the timestamp, configured to be shared by the user to verify the user's ownership of an object associated with the object information, generating a combination certificate hash value from a hash function including the combination certificate as an input, encrypting the combination certificate hash value with an issuer private key, defining an issuer signature, signing the combination certificate with the issuer signature, defining a signed combination certificate, recording the signed combination certificate to the digital certificate smart contract, and sending the combination certificate to the user.

In some embodiments the method may further comprise receiving hashed second user identification information associated with a second user and a derivative of the object information, defining a derivative object information, recording to a second digital certificate smart contract deployed at a second digital certificate smart contract address on a second blockchain network the hashed second user identification information and the derivative object information and a timestamp of when the hashed second user identification information and the derivative object information were received, defined as a received timestamp, signing the second digital certificate smart contract with a second issuer signature, generating a second combination certificate configured to be shared by the second user to verify the second user's ownership of a derivative object associated with the derivative object information, and sending the second combination certificate to the second user. Additionally, the method may further comprise receiving hashed third user identification information associated with a third user and the derivative object information, recording to a third digital certificate smart contract deployed at a third digital certificate smart contract address on a third blockchain network the hashed third user identification information and the derivative object information and a timestamp of when the hashed third user identification information and the derivative object information were received, defined as a received timestamp, signing the third digital certificate smart contract with a third issuer signature, generating a third combination certificate configured to be shared by the third user to verify the third user's ownership of a derivative object associated with the derivative object information, recording to the second digital certificate smart contract an indication that the second digital certificate smart contract is expired; and sending the third combination certificate to the third user.

In some embodiments the method may further comprise receiving hashed third user identification information associated with a third user and a second derivative of the object information, defining a second derivative object information, recording to a third digital certificate smart contract deployed at a third digital certificate smart contract address on a third blockchain network the hashed third user identification information and the second derivative object information and a timestamp of when the hashed third user identification information and the second derivative object information were received, defined as a received timestamp, signing the third digital certificate smart contract with a third issuer signature, generating a third combination certificate configured to be shared by the third user to verify the third user's ownership of a derivative object associated with the second derivative object information, and sending the third combination certificate to the third user. The second derivative object information may exist concurrently with the derivative object information.

Furthermore, embodiments of the invention may be directed to a system for issuing blockchain-based digital certificates comprising a processor, a data store positioned in communication with the processor; and a network communication device positioned in communication with each of the processor, the data store, and a network. The network communication device may be operable to receive from a user hashed user identification information, object information, and a user public key. The processor may be operable to record to a digital certificate smart contract deployed at a digital certificate smart contract address on a blockchain network the hashed user identification information and object information and a timestamp of when the hashed user identification information and the object information were received, defined as a received timestamp, and to sign the digital certificate smart contract with an issuer signature. Furthermore, the system may be operable to perform a user identity verification process to confirm a user identity, comprising the network communication device obtaining each of a sealed user record address, a sealed verification record address, and a token from a user certification record address at the user certification record address, the network communication device retrieving hashed user identification information from a sealed user record at the sealed user record address, defining retrieved user identification information, the processor decrypting the received user identification information using the user public key, defining decrypted user identification information, the processor comparing the decrypted user identification information with the retrieved user identification information, the network communication device retrieving a hashed verification record from a sealed verification record at the sealed verification record address, defining a retrieved verification record, and the processor determining if the token from the user certification record address is valid. The processor may be further operable to, upon determining the token from the user certification record address is valid, generate a generated verification record comprising the retrieved user identification information and the token; generate a hashed verification record by applying a hash function to the generated verification record, compare the hashed verification record with the retrieved verification record, and confirm a user identity by determining the decrypted user identification information and the retrieved user identification information are at least a partial match and the hashed verification record and the retrieved verification record are at least a partial match.

Additionally, the processor may be operable to, upon the user identity being confirmed, generate a combination certificate configured to be shared by the user to verify the user's ownership of an object associated with the object information. The network communication device may further be operable to send the combination certificate to the user.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an illustration of the blockchain account types and interactions.

FIG. **2** is an illustration of the user registration and certification process, according to an embodiment of the invention.

FIG. **3** is an illustration of the user validation process, according to an embodiment of the invention.

FIG. **4** is a reference implementation of Seal and Certification smart contracts, according to an embodiment of the invention.

FIG. **5** is an illustration of hardened derivation of a child key in a Hierarchical Deterministic wallet as proposed in BIP0032.

FIG. **6** is an illustration of a toughened HD wallet (an improvement over the Hierarchical Deterministic wallet as proposed in BIP0032), according to an embodiment of the invention.

FIG. **7** is an illustration of the toughened and hardened derivation of a child key, according to an embodiment of the invention.

FIG. **8** is an illustration of the examples of toughened and hardened child key derivations, according to an embodiment of the invention.

FIG. **9** is an illustration of the user interactions with multiple blockchain networks, according to an embodiment of the invention.

FIG. **10** is an illustration of the scenarios for using wallet keys with different blockchain networks, according to an embodiment of the invention.

FIG. **11** is an illustration of the examples of roles based access control with different roles assigned to different users, according to an embodiment of the invention.

FIG. **12** is an illustration of the examples of roles based access control, with role assignment to individual keys belonging to a user, according to an embodiment of the invention.

FIG. **13** is a schematic diagram of a blockchain identity and access management system (B-IAM), according to an embodiment of the present invention.

FIG. **14** is an illustration of the interactions between the B-IAM system and other blockchain networks and decentralized applications, according to an embodiment of the present invention.

FIG. **15** is an illustration of the process to generate a unique document or object identifier, according to an embodiment of the invention.

FIG. **16** is an illustration of the timeline of ownership and custody of a document or object, according to an embodiment of the invention.

FIG. **17** is an illustration of the certificate generation process, according to an embodiment of the invention.

FIG. **18** is an illustration of the process for issuing a certificate for proof of existence, ownership, custody and integrity, according to an embodiment of the invention.

FIG. **19** is an illustration of the certificate verification process, according to an embodiment of the invention.

FIG. **20** is an illustration of the process for verifying or proving existence, ownership, custody and integrity of a document or object, according to an embodiment of the invention.

FIG. **21** is an illustration of an example of a combined proof of ownership, existence, custody and integrity certificate, according to an embodiment of the invention.

FIG. **22** is an illustration of levels of abstraction for a combined proof of ownership, existence, custody and integrity certificate, according to an embodiment of the invention.

FIG. **23** is an illustration of the process for issuing and verifying certificates for multiple documents or objects on multiple blockchains linked to the same user, according to an embodiment of the invention.

FIG. **24** is an illustration a sequential model of document/object existence where the derived forms of a document/object are recorded on multiple blockchains, according to an embodiment of the invention.

FIG. **25** is an illustration a concurrent model of document/object existence where the derived forms of a document/object are recorded on multiple blockchains, according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Those of ordinary skill in the art realize that the following descriptions of the embodiments of the present invention are illustrative and are not intended to be limiting in any way. Other embodiments of the present invention will readily suggest themselves to such skilled persons having the benefit of this disclosure. Like numbers refer to like elements throughout.

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following embodiments of the invention are set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

In this detailed description of the present invention, a person skilled in the art should note that directional terms, such as "above," "below," "upper," "lower," and other like terms are used for the convenience of the reader in reference to the drawings. Also, a person skilled in the art should notice this description may contain other terminology to convey position, orientation, and direction without departing from the principles of the present invention.

Furthermore, in this detailed description, a person skilled in the art should note that quantitative qualifying terms such as "generally," "substantially," "mostly," and other terms are used, in general, to mean that the referred to object, characteristic, or quality constitutes a majority of the subject of the reference. The meaning of any of these terms is dependent upon the context within which it is used, and the meaning may be expressly modified.

Referring to FIGS. **1**-**12**, an Identity and Access Management system for Blockchain Interoperability according to an embodiment of the present invention is now described in detail. Throughout this disclosure, the present invention may be referred to as a Blockchain Identity and Access Management (B-IAM) system, a blockchain identity system, blockchain access management system, a blockchain access control system, a device, a system, a product, and a method. Those skilled in the art will appreciate that this terminology is only illustrative and does not affect the scope of the invention. Moreover, those skilled in the art will appreciate that all processes described herein may be performed by a computing device comprising, but not limited to, a network communication device operable to communicate across a network, such as a wide area network, including the Internet, a processor in communication with the networking communication device and operable to perform computing functions, and a data store capable of receiving, storing, and providing information to each of the network communication device and the processor.

Referring now to FIG. **1**, for example, and without limitation, blockchain account types and interactions between them, are described in more detail. Blockchain is a distributed and public ledger which maintains records of all the transactions. A blockchain network **100** is a truly peer-to-peer network and it does not require a trusted central authority or intermediaries to authenticate or to settle the transactions or to control the network infrastructure. Users can interact and transact with the blockchain networks through Externally Owned Account (EOAs) **110**, which are owned and controlled by the users. Each EOA **110** has an account address **102**, account public-private keys **104** and a balance **106** (in certain units of a Cryptocurrency associated with the Blockchain network) associated with it. EOAs do not have any associated code. All transactions **120** on a blockchain network are initiated by EOAs. These accounts can send transactions to other EOAs or contract accounts. Another type of accounts support by second generation programmable Blockchain platforms are the Contract Accounts **108**. A Contract Account **108** is created and owned by an EOA **110**, is located at a contract address **112**, and is controlled by the associated contract code **114** which is stored with the contract account **108**. Additionally, the contract account **108** may comprise a balance **116**, which may be identical to the balance **106** of the EOA **110**. The contract code **112** execution is triggered by transactions **118** sent by EOAs or messages sent by other contracts.

An embodiment of the invention provides a system and associated methods for securely linking blockchain accounts to real users. Referring to FIG. **2**, the user registration and certification process, for securely linking blockchain accounts to real users, is described in more detail. User registration process is done to link a real user **250** to one or more blockchain accounts. For the registration process, the user **250** either uses a registration application either on mobile or a desktop computer. In the registration application, the user provides the identification information (including fields such as name, address, date of birth and other identification information), scanned identification card (such as a driver license, passport or other types of ID cards), fingerprints and other biometric data, user photo, and any other type of data that can be used to identify the user. Each data field provided by the user in the registration application (collectively referred to as the 'UserData' **256**) is hashed using a one-way hash function **258**, generating hashed data **260**. The registration application then creates a new smart contract from this hashed data **260**, which is referred to as the 'Seal Contract' **262**. The transaction to create this new Seal Contract **262** on the blockchain network is signed by the user's private key. The Seal Contract **262** maintains a record of the hashed user data and the user's address on the blockchain network. A separate private and/or permissioned blockchain **254** may be used for user identity management, where the Seal Contract is deployed. When the transaction to create the new Seal Contract is mined, the user gets an address of the contract, which is referred to as the 'Sealed UserRecord Address' **264**. This completes the user registration process.

The next step is the certification process, in which the user provides the 'UserData', digitally signed and hashed 'UserData', and the 'Sealed UserRecord Address' **266** to a certification authority **252**. The data is signed by the user's private key. This data may be shared with the certification authority **252** over an encrypted and secure channel, so that only the certification authority can decrypt and access the data. The certification authority **252** then verifies if the UserRecord has been created and sealed by the user **250** and if the user own's the record and the associated Seal Contract **262** by performing a certification process **268**. The steps involved in the certification process **268** may include, as follows:

1. Get Hash(UserData) from Sealed UserRecord Address
2. Decrypt Sign(Hash(UserData)) with user's public key
3. Get user's fingerprints and/or biometric data, user photo and combine with other data fields from UserData to recreate UserData and then generate its hash: Hash(UserData').
4. If outputs of steps 1, 2, 3 above are equal then create verification record as follows:

VerificationRecord=(Hash(UserData)+Token)

5. Create a new Seal Contract with Hash(VerificationRecord) **274** as the input data.

The transaction to create this new Seal Contract **270** on the blockchain is signed by the certification authority's private key. When the transaction to create the new Seal Contract **270** is mined, the certification authority **252** gets an address of the contract, which is referred to as the 'Sealed VerificationRecord Address' **276**.

Next the certification authority creates a new smart contract, referred to as the 'Certification Contract' **272** by providing the Sealed UserRecord Address **264**, Certification Token and Sealed VerificationRecord Address **276** as the input data **278** to the contract. When the transaction to create the Certification Contract **272** is mined, the certification authority gets an address of the contract, which is referred to as the 'Certification Record Address' **280**, and shares this address with the user. This completes the user certification process. The certification process establishes the ownership of the blockchain account (and its associated public-private key-pairs) to a real user **250** whose identity is verified by the certification authority **252**. The certification token can be used to set a validity or a timeout period for a key-pair. After the timeout of the certification of key-pair, the certification process has to be done again. This certification renewal process adds additional security and prevents against any misuse of keys.

Referring to FIG. **3**, a method aspect of the present invention for user validation is described in more detail. A certified user **250** can then interact with blockchain applications (either smart contracts or decentralized applications). These blockchain applications may be deployed on different blockchain networks **300**. When a blockchain application requests the identity of a certified user **250**, the user sends the CertificationRecord Address and the signed and hashed UserData **260** to the blockchain application. The blockchain application then carries out the validation process **308**. The steps involved in the validation process **308** may include, as follows:

1. Get Sealed UserRecord Address **304** from CertificationRecord Address **302**
2. Get Hash(UserData) from Sealed UserRecord Address **304**
3. Decrypt Sign(Hash(UserData)) with user's public key
4. Compare outputs of steps 2 and 3. If equal it proves that the UserRecord has been created and sealed by the user and the user own's the record and its seal.
5. Get Sealed VerificationRecord Address **306** from CertificationRecord Address
6. Get Hash(VerificationRecord) from Sealed VerificationRecord Address **306**
7. Get Token from CertificationRecord Address and check if it is valid
8. Recreate verification record: VerificationRecord' = (Hash(UserData)+Token) and generate its hash: Hash(VerificationRecord')
9. Compare outputs of steps 6 and 8. If equal, it proves that the user has been authenticated by the certification authority.

The above steps complete the user validation process **308**. Once a user has been validated, the blockchain application may generate an application specific session token **310** (with a short validity), so that the user can interact **312**, **314** further with the application without going through the validation process again for each transaction. A reference implementation of Seal **350** and Certification **352** smart contracts, according to an embodiment of the invention, is shown in FIG. **4**.

An embodiment of the invention provides a system and associated methods for key generation and management, where a user can generate a large number of keys in a deterministic manner for use on a single blockchain network or across multiple blockchain networks.

Referring now to FIG. **5**, a hardened derivation of a child key in a Hierarchical Deterministic (HD) wallet as proposed in the Bitcoin Improvement Proposal (BIP0032) is described in more detail. An HD wallet contains a hierarchy of keys which are derived in a tree structure. The master key in an HD wallet is derived from a single root seed. HD wallets use child key derivation (CKD) functions to derive children keys from parent keys. The child private key **212** and child public key **214** are derived from the parent keys, and a chain code **202** which adds extra bits of entropy. The inputs to a CKD function **206** are a public or private key **200**, a chain code **202** and an index **204**. The public or private key **200** and chain code are combined to create an extended key (public or private). With a private extended key it is possible to derive the entire branch of keys in the sub-tree structure rooted at the private extended key. Whereas, with a public extended key only the public keys in the entire branch can be derived. While the ability to derive the entire branch of public keys is very useful, however, it comes at a potential risk of leaking the entire tree structure. This risk is due to the fact that the extended public key also contains the chain code. If the extended public key and a child private key descending from it are revealed, an attacker can use them to generate the parent extended private key. With this parent extended private key all the child private and public keys may be created. To counter this risk, a method of generation of 'hardened' keys is provided in HD wallet where a parent private key **200** is used to derive the child chain code **216** instead of the parent public key. A limitation of the 'hardened' child key derivation mechanism in BIP0032 is that it does not give any protection in the case of a leak of a private extended key. If a private extended key is leaked the entire sub-tree of keys can be derived.

Referring to FIG. **6**, a method aspect of the present invention for key generation is described in more detail. We present an extension to Hierarchical Deterministic (HD) wallets, which adds additional levels of security to counter leak of private extended keys. For each user a 'Super HD Wallet' is created using the HD wallet mechanism described above. More specifically, a primary seed **400** that may comprise a parent public or private key, a parent chain code, and an index, may be received and an enhanced hierarchical deterministic wallet comprising an enhanced parent public key and an enhanced parent private key pair **402** may be generated by applying a CKD function to the primary seed **400**. Additionally, the enhanced hierarchical deterministic wallet may further comprise one or more enhanced primary child public/private key pairs **404**, **408**, **410**, where the enhanced primary child public keys is derived from the enhanced parent public key and the enhanced primary child private key is derived from the enhanced parent private key. Moreover, the enhanced hierarchical deterministic wallet may further comprise one or more enhanced secondary child public/private key pairs **412**, **414**, **416**, **418**, **420**,**422** derived enhanced primary child public/private key pairs **404**, **408**, **410**.

Next, for each blockchain network, separate Toughened HD Wallets' are created. The child keys in a 'Toughened HD Wallet' depend not just on their parent but also on the corresponding parent in the 'Super HD Wallet' (the key at the same path in the Super HD wallet as the parent key). More specifically, a first secondary seed **424**, similar to the primary seed **400**, may be received and a first toughened hierarchical deterministic wallet may be generated by deriving a first toughened parent public/private key pair **426** from the first secondary seed **424** and a first toughened primary child public/private key pair **428** from the first toughened parent public/private key pair **426**. A second toughened primary child public/private key pair **430** may also be derived from the first toughened parent public/private key pair **426**. Indeed, any number of toughened primary child public/private key pairs **432** may be derived. Additionally, first and second toughened secondary child public/private key pairs **434**, **436** may be derived from the first toughened primary child public/private key pair **428**, first and second toughened secondary child public/private key pairs **438**, **440** may be derived from the second toughened primary child public/private key pair **430**, and any number of toughened secondary child public/private key pairs **442**, **444** may be derived from toughened primary child public/private key pairs **432**.

While a single toughened hierarchical deterministic wallet is depicted, second, third, and any number of toughened hierarchical deterministic wallets, generated by respective secondary seeds and comprising toughened parent public/private key pairs and any number of primary, secondary, tertiary, and any hierarchically subsequent toughened child public/private key pairs, is contemplated and included within the scope of the invention.

The super or enhanced HD wallet keys can be derived using the same or similar approaches as in BIP32 for this. This "super" or "enhanced" HD wallet is differentiated from the other "toughened" wallets used for each blockchain network further because the "super" or "enhanced" wallet is generated for each user (e.g., are linked to the user identity) whereas "toughened" wallets are generated separately for each blockchain network account that the user's account participates in.

Referring to FIG. **7**, a method aspect of the present invention for the toughened and hardened key derivation will now be discussed in detail. In a normal HD Wallet the Child Key Derivation functions for private and public keys are as follows:

CKDpriv((kpar, cpar), i)→(ki, ci)

CKDpub((Kpar, cpar), i)→(Ki, ci)

where, child private key (ki) and child public key (Ki) depend on their parents keys and the parent chain code.

In a 'Toughened HD Wallet' enhanced child key derivation functions are proposed as follows:

CKDprivTough((kpar, cpar), kparsuper, i)→(ki, ci)

CKDpubTough((Kpar, cpar), Kparsuper, i)→(Ki, ci)

where, child private key (ki) **514** and child public key (Ki) **516** depend on their parents keys **502**, parent chain code **506** and the corresponding key from the Super HD Wallet **502** (i.e., key at the same path as their parent), as modified by a CKD function **504**. Additionally, an index number **508** may also be included in as an input to the CKD function **504**. Moreover, in some embodiments, the CKD function **504** may be operable to generate a number of bits that is greater than the number of bits necessary to generate the child private key **514**. For example, in the present embodiment, the CKD function **504** may generate 512 bits, where 256 bits are required for the child private key **514**. Accordingly, a subset of the 512 bits generated by the CKD function **504**, e.g., the "left" 256 bits **510**, as is known in the art, may be used to generate the child private key **514**. Additionally, the "right" 256 bits **512**, as is known in the art, but in any case the bits not used to generate the child private key **514**, may be utilized as a child chain code **518** for the derivation/generation of toughened child public/private key pairs.

FIG. **8** shows examples of using reference implementations of toughened and hardened child key derivation functions.

An embodiment of the invention provides a system and associated methods for maintaining user identity across multiple blockchain networks. Referring to FIGS. **9** and **10**, a method aspect of the present invention for maintaining user identity across multiple chains is described in more detail. For each user a 'Super HD Wallet' **700** is created **714** and separate 'Toughened HD Wallets' **702**, **704** are created **716**, **718** for separate blockchain networks **612/708**, **614/710**. The user registration process **624** needs to be done only once for a user, generating a seal contract **600** as described hereinabove. The certification process **626/720** can be carried out once for the Super HD wallet and then for each Toughened HD wallet, generating a certification contract **602** as described hereinabove. Once a master key in a HD wallet (Super or Toughened) has been certified for a user, the ownership of a child key can be verified by sharing the derivation path from master to child key without the need to through the whole certification and validation process again when the master key is already certified. To use a child key from a Toughened HD wallet on a blockchain network, the user creates a new blockchain account by importing **722**, **724** the key **608**, **610** from the Toughened HD Wallets **702**, **704**. The identity of the user may be verified **726**, **728** by the blockchain networks **612/708**, **614/710** accessing **622**, **618** the certification contract **602**.

The derived child keys in a 'Toughened HD wallet' can be used in several ways, described as follows:

1) In one embodiment, the child public keys can be used for receiving funds and the private keys are required for spending funds.

2) In another embodiment, new child keys can be derived and used for each session or each transaction.

3) In another embodiment, specific roles and privileges can be assigned to specific child keys or specific sub-trees in a Toughened HD wallet. A smart contract **604** on the user identity blockchain can maintain a mapping from the child keys to specific roles and privileges. The smart contract **604** may function to ensure requests **620**, **616** made by the respective blockchain networks **612**, **614** comply with the specific roles and privileges made for those blockchain networks.

4) In another embodiment, a smart contract can be used to maintain a mapping from the child keys to their respective timeout periods.

5) In another embodiment, a smart contract can be used to control key reuse, where a key can be allowed to be used for a limited number of transactions only.

6) In another embodiment, smart contracts can be used for information sharing on the user accounts across different blockchain networks.

The proposed methods of maintaining user identity across multiple blockchain networks, can prevent a rogue user from accessing blockchain applications by impersonating a real user. While a rogue can try to generate one or more HD wallets (with normal or hardened keys) and attempt to access blockchain applications on different chains, however, since these applications require the user's master keys to be certified, they will reject access to the user when the validation process is performed as there will be no linked Super HD wallet for which a certification exists on the identity blockchain.

An embodiment of the invention provides a system and associated methods for role-based access control in blockchain applications. Referring to FIGS. **11** and **12**, a method aspect of the present invention for role-based access control is described in more detail. Role-based access control for blockchain applications is used to restrict access to authorized users. The role-based access control system allows defining roles and policies which control access to the blockchain applications and their associated smart contracts. A role is a set of permissions which grant access to particular resource of a blockchain application (for example, a state variable or a function in the smart contract, or a collection of smart contracts). Policies are attached to roles which define the permissions for the roles. The information about roles and policies for a blockchain application may be maintained in a smart contract on the identity blockchain. Role assignments maybe done in the following ways:

1) In one embodiment, as shown in FIG. **11**, where a blockchain application has a single smart contract **750** (that includes a set of state variables **752** and functions **754**), the role assignments may be done to specific state variables **752** and functions **754**. For example, a user in the role of a contract owner **762** would have access to read and update all state variables **752** and access all the functions **754** of the smart contract **750**. Whereas, other users **764**, **768** may have access to only a subset of the state variables and functions.

2) In another embodiment, as shown in FIG. **11**, where a blockchain application has multiple smart contracts **756**, **776** the role assignments may be done at the level of smart contracts. For example, a user in the role of the application owner **770** would have access to read and update all state variables **758**,**778** and access all the functions **760**, **780** in all the smart contracts **756**, **776** in the application. Whereas, other users **772**, **774** may have access to only certain smart contracts in the application.

3) In another embodiment, as shown in FIG. **12**, different roles may be assigned to different child keys belonging a certified user **800**. For example, a derived key at path m/0/1 in the user's toughened HD wallet **802** may be allowed to access all the state variables **806** and functions **810** in a smart contract **804** and, alternatively, all state variables **814**, **814'** and functions **816**, **816'** in smart contracts **812**, **812'**, whereas a derived key at path m/0/0/1 in the user's toughened HD wallet **802** may be allowed to access only a subset of state variables and functions, e.g. either state variables **814** and functions **816** of smart contract **812** or state variables **814'** and functions **816'** of smart contract **812'**.

4) In another embodiment, additional constraints (at the contract or application-level) may be defined within the policies attached to roles. For example, in a case of a voting application on the blockchain, a user may be allowed to vote only once (i.e., send a transaction to the vote function of the smart contract only once).

Referring to FIG. **13**, a blockchain identity and access management system (B-IAM) system according to an embodiment of the present invention is now described in detail. The B-IAM system's infrastructure layer **940** comprises a blockchain network **948**, a decentralized storage platform **946**, decentralized messaging platform **944** and cloud infrastructure **942**. All the smart contracts related to user identity management (such as the Seal Contract, Certification Contract, Roles & Privileges Contract) deployed on the blockchain network **948**. For **948**, a blockchain platform such as Ethereum can be used. The decentralized messaging platform **944** is used for messaging between the decentralized applications (Dapps), which are built on the B-IAM system. For **944**, a decentralized messaging platform such as Whisper, can be used. Whisper messages are transient in nature and have a time-to-live (TTL) set. Each message has one or more topics associated with it. The Dapps running on a blockchain node inform the node about the topics to which they want to subscribe. Whisper uses topic-based routing where the nodes advertise their topics of interest to their peers. Topics are used for filtering the messages which are delivered to a node which are then distributed to the Dapps running on the blockchain node. The decentralized storage platform **944** is used for storing user data such as user photos, and scanned identity documents. For **946**, a decentralized storage platform such as Swarm can be used. Swarm is a decentralized storage platform and content distribution service for the Ethereum blockchain platform. Swarm is a peer-to-peer storage platform which is maintained by the peers who contribute their storage and bandwidth resources. Swarm has been designed to dynamically scale up to serve popular content and has a mechanism to ensure the availability of the content which is not popular or frequently requested. The cloud infrastructure **942**, is used for collection, storage and analysis of application usage data.

The B-IAM system's platform and application services layer **932** comprises Integration Services **914**, Identity & Authentication Services **920**, User Registration & Certification Services **926**, Data Management & Analytics Services **934**. The Integration Services **914**, comprise Inter-Blockchain and Intra-blockchain Messaging Services **916**, and various connectors for applications, cloud services and other blockchain networks **918**. The Identity & Authentication Services **920** comprise a User Identity & Access Management Service **924**, and a B-IAM portal **922**. The B-IAM portal **922** allows users **900** to access and monitor their identity data recorded in the B-IAM system and view identity requests made by different applications. The User Registration & Certification Services **926** comprise a User Registration Service **930** (which is used for the process flow as shown in FIG. **2**) and a User Certification Service **928** (which is used for the process flow as shown in FIG. **3**). The Data Management & Analytics Services **934**, are deployed on the cloud infrastructure **942**. These include an analytics service **936**, reporting service **938**, and an alerting service **939**. The analytics service **936**, can analyze multi-blockchain behavior of a user account to ensure compliance. It is contemplated and included within the scope of the invention that all of these platforms and applications services are operable on a computerized device comprising a processor, a network communication device, and a data storage device as described hereinabove.

The B-IAM system can be used for providing identity, access management and authentication services for a wide range of applications **904**. Some exemplary applications that can benefit from the B-IAM system include an identity verification application **906**, access control application **908** and a blockchain-based payments application **910**. All of these may communicate with third party devices and applications **902** that identifies and/or authenticates the users **900**.

Referring to FIG. **14** the interactions between the B-IAM system **850** and other blockchain networks **852** and decentralized applications **874**, according to an embodiment of the present invention are now described in detail. The B-IAM system can be used to provide user identity and access management services for various decentralized applications deployed on different blockchain networks. The B-IAM allows a user to work on multiple blockchain networks, or multiple applications deployed on the same blockchain networks, while maintaining the same identity. The blockchain network **852** can communicate **858** with the B-IAM system using an Inter-Blockchain Messaging protocol **856**. The blockchain network **852** can also send usage data **884** (such as application usage and user interactions data) to the B-IAM system. Applications deployed on a blockchain network **852** are either in the form of smart contracts **876** or Dapps **874**. A smart contract is a piece of code which is deployed on the blockchain network and is uniquely identified by an address. While smart contracts can directly be used by end users **882** who can send transactions or calls to the smart contracts through blockchain clients, however, to provide a more user-friendly interface to smart contracts, Dapps can be developed and applied over these smart contracts. A Dapp **874** includes one or more associated smart contracts **876**, a front-end user interface **880** (which is typically implemented in HTML and CSS) and a back-end **878** (which is typically implemented in JavaScript). Users can submit transactions to the smart contract **876** associated with a Dapp from the Dapp's web interface itself. The Dapp's web interface forwards the transactions to the blockchain platform **852** and displays the transaction receipts or state information in the smart contracts in the web interface. A Dapp is deployed on a blockchain node **854** which serves the Dapp's web-based user interface. The Dapp logic is controlled by the associated smart contracts **876** which are deployed on the blockchain platform **852**. Dapps which have special storage requirements can make use of a decentralized storage platform (such as Swarm). Similarly, Dapps which have special messaging requirements can leverage a decentralized messaging platform (such as Whisper). A blockchain node **854** typically comprises a blockchain client **860** that sends transactions to the blockchain network **852**, a smart contracts compiler **862**, a decentralized storage client & local store **864**, and a decentralized messaging client **868**. While the smart contracts are deployed on the blockchain network, Intra-blockchain messaging **870** (over a decentralized messaging platform) and decentralized storage/retrieval requests **872** (over a decentralized storage platform) work off the chain as they do not require a consensus on the blockchain.

Referring to FIG. **15**, a method for generating a unique document or object identifier, according to an embodiment of the present invention is now described in detail. For a document or digital object **1002** (such as a word processing document, such as a Microsoft Office Word document, PDF or a zip file), the contents **1004** of the document or object are input to a cryptographic hash function **1006** (such as SHA-3, although all other cryptographic hash functions as are known in the art are contemplated and included within the scope of the invention) to generate a unique identifier **1008**. The identifier **1008** for a document of digital object is specific to the contents of the document or object and any change in the document or object contents changes the cryptographic hash. For a physical object **1012** (such as a diamond, phone, car, watch, keys) an object identifier (such as a laser inscription in a diamond, phone IMEI number, car engine or chassis number, an engraved number on a key) associated with the physical object **1012** is input to the cryptographic hash function **1006** to generate the unique identifier **1008**.

Referring to FIG. **16**, a timeline of ownership and custody of a document or object, according to an embodiment of the present invention is described in more detail. A document or object **1024** is owned or controlled by a user or company

1020 at a given point in time or location. By recording the ownership and custody of the document or object along with the timestamp and/or location, a timeline can be created such that points 1026, 1028, 1030 on the timeline establish the ownership and custody of the document or object.

An embodiment of the invention provides a system and associated methods for issuing blockchain-based digital certificates which serve as combined Proofs of Existence, Ownership, Custody and Integrity of documents or objects (digital or physical), defined as a combination certificate. Referring to FIG. 17, a combination certificate generation process for a document or object, according to an embodiment of the present invention is described in more detail. The entities and systems involved in the combination certificate generation process include a user 1052 who is the owner or custodian of a document or object 1050, an issuer 1054 who issues the blockchain-based digital certificate, and a blockchain network 1056 on which the smart contracts for issuing and recording digital certificates are deployed. The combination certificate generation process begins with the user 1052 sharing the user and document/object identification details in step 1062 with the issuer 1054. The issuer 1054 records the user identifier, object identifier, timestamp and, optionally, a location of the user in a smart contract deployed on the blockchain network 1056 in step 1064, and creates a combination certificate 1080. The combination certificate 1080 is sent by the issuer 1054 to the user 1052 in step 1066. The user 1052 can share 1068 the combination certificate 1080 with a consumer or third party 1058. The consumer or third party 1058 can get the combination certificate 1080 verified from a verification authority 1060. The verification authority 1060 may be the same institution as the issuer 1054 or may be a third party. The consumer or third party 1058 sends the combination certificate 1080 for verification to the verification authority 1060 in step 1070. The verification authority 1060 looks up the combination certificate 1080 on the blockchain network 1056 and verifies the certificate integrity, authenticity and validity in step 1072. A verification response is sent back to the consumer or third party 1058 by the verification authority 1060 in step 1074.

It is contemplated and included within the scope of the invention that embodiments of the invention may be operable to interact with a blockchain network 1056 as presented herein, including, but not limited to, proof-of-work systems, proof-of-stake systems, and hybrid systems that are a combination of proof-of-work and proof-of-stake systems. Furthermore, it is contemplated and included within the scope of the invention that the invention may be operable to interact with a public ledger system other than a blockchain network.

Referring to FIG. 18, and additionally referring to FIGS. 2 and 3, the process for issuing a combination certificate for proof of existence, ownership, custody and integrity, according to an embodiment of the present invention is described in more detail. A certified user 1052 who is the owner or custodian of a document or object 1050, sends the user's CertificationRecord address, digitally signed and hashed 'UserData', hash of the document contents or object identifier, and user location to the issuer 1054 in step 1102. The issuer 1054 then verifies the user identity in step 1104 by performing a user validation process 1106. The steps involved in the user validation process 1106 may include, as follows:

1. Get Sealed UserRecord Address 1122 from CertificationRecord Address 1120
2. Get Hash(UserData) from Sealed UserRecord Address 1122
3. Decrypt Sign(Hash(UserData)) with user's public key
4. Compare outputs of steps 2 and 3. If at least a partial match it proves that the UserRecord has been created and sealed by the user and the user own's the record and its seal.
5. Get Sealed VerificationRecord Address 1124 from CertificationRecord Address 1120
6. Get Hash(VerificationRecord) from Sealed VerificationRecord Address 1124
7. Get Token from CertificationRecord Address and check if it is valid
8. Recreate verification record: VerificationRecord'=(Hash(UserData)+Token) and generate its hash: Hash(VerificationRecord')
9. Compare outputs of steps 6 and 8. If at least a partial match, it proves that the user has been authenticated by the certification authority.

In the comparisons performed at steps 4 and 9, at least a partial match is required. The partial match may be based on satisfying one or more criteria, including, but not limited to, matching of a subset of fields in a record, longest prefix match, longest sub-string match or fields in the record satisfying a range query. In some embodiments, all the criteria must be satisfied for the comparison to be deemed successful and demonstrating, in the case of step 4, that the UserRecord has been created and sealed by the user and the user own's the record and its seal and, in the case of step 9, that the user has been authenticated by the certification authority.

The above steps complete the user validation process 1106. Next, the combination certificate is created at 1110 as follows:

1. Create a combination certificate containing user's certification record, document/object identifier or hash, timestamp and, optionally, location data.
2. Sign the combination certificate digitally
3. Record a cryptographic hash of the combination certificate in a Digital Certificate Smart Contract 1126 on the blockchain network 1056.

The issuer 1054 may receive a DigitalCertificate Address of the Digital Certificate Smart Contract 1126 on the blockchain network 1056 at step 1114. The issuer 1054 then sends the combination certificate 1080 containing the DigitalCertificate Address and other certificate details to the user 1052 in step 1116.

Referring to FIG. 19, the certificate verification process for a document or object, according to an embodiment of the present invention is described in more detail. The consumer or third party 1058 can verify a combination certificate 1080 with a verification authority 1060. The consumer or third party 1058 sends the combination certificate 1080 to the verification authority 1060 in step 1140. A mobile or web application may be used in the certificate verification process where a user can submit the combination certificate in the mobile or web application for verification. The verification authority 1060 looks up the combination certificate 1080 on the blockchain network 1056 in step 1142 and then verifies the combination certificate 1080 at 1144 as follows:

1. Verify combination certificate integrity: Check if the combination certificate hash matches the hash recorded in the smart contract.
2. Verify combination certificate authenticity: Verify if the combination certificate is signed by the issuer.
3. Verify combination certificate validity: Check if the combination certificate is valid and active (i.e. not revoked or expired).

Once the combination certificate **1080** is verified, the verification authority **1060** sends a verification response **1148** to the consumer or third party **1058**.

Referring to FIG. **20**, the process for verifying or proving existence, ownership, custody and integrity of a document or object, according to an embodiment of the present invention is described in more detail. A user **1052** who is the owner or custodian of a document or object **1050**, can prove the existence, ownership, custody and integrity of a document or object, by sharing the DigitalCertificate Address, digitally signed and hashed 'UserData', and the document/object identifier (hash of the document contents or the object identifier) with the verification authority **1060**. The verification authority **1060** then looks up the certificate on the blockchain network **1056** and verifies the user identity and existence, ownership, custody and integrity of the document or object **1050** at **1164** as follows:

1. Get CertificationRecord Address **1120** from the DigitalCertificate Address **1126**
2. Get Sealed UserRecord Address **1122** from CertificationRecord Address **1120**
3. Get Hash(UserData) from Sealed UserRecord Address **1122**
4. Decrypt Sign(Hash(UserData)) with user's public key
5. Compare outputs of steps 3 and 4. If at least a partial match it proves that the UserRecord has been created and sealed by the user and the user own's the record and its seal.
6. Get Sealed VerificationRecord Address **1124** from CertificationRecord Address **1120**
7. Get Hash(VerificationRecord) from Sealed VerificationRecord Address **1124**
8. Get Token from CertificationRecord Address and check if it is valid
9. Recreate verification record: VerificationRecord'=(Hash(UserData)+Token) and generate its hash: Hash(VerificationRecord')
10. Compare outputs of steps 7 and 9. If at least a partial match, it proves that the user has been authenticated by the certification authority.
11. Get document/object hash from the DigitalCertificate contract **1126** and compare with the hash provided by the user. If the two hashes match at least partially, the document/object being presented by the user is the same as the one recorded in the certificate.
12. If the user and document/object are successfully verified, return the User identifier, Object identifier, Time, Location recorded in the combination certificate **1126**.

FIG. **21** is an illustration of an example of a combined proof of ownership, existence, custody and integrity certificate, according to an embodiment of the invention. The digital certificate **1200** includes a certificate identifier **1202**, a certificate URL **1204** (which is specific to the issuer or the platform issuing the certificate), the document or object name **1206**, the document or object identifier **1208**, the name of the owner or custodian **1210** of the document or object, the user (owner or custodian) identifier **1212**, date and time of generation of the certificate **1214** and location of the user when the certificate was issued **1216**.

Referring to FIG. **22**, levels of abstraction for a combined proof of ownership, existence, custody and integrity certificate, according to an embodiment of the invention, are described in more detail. A combination certificate may take many forms when generated for different purposes or views (such as full, partial or redacted) depending on privacy and security constraints. A combination certificate record **1306** may have multiple levels of abstraction and detail depending on how and who is viewing or verifying it. For example, in the case of a combination certificate that represents the academic credentials of a student, a potential employer can see some details on the GPA of a graduate student but not how long it took to graduate, whereas, a graduate school could see the reference letters or list of courses and individual grades. Similarly, in the case of a combination certificate that represents the ownership and transfer record of a house, one level of detail can be shown to a buyer and another level of detail can be shown to a lender. In the least abstract form, a certificate view **1304** may make all the combination certificate fields visible to a user **1312**. Whereas in the most abstract form **1300**, only a subset of fields in the combination certificate may be visible to the user **1308**. Furthermore, an intermediate abstract form **1302** may include a subset of fields that varies in scope in terms of the quantity and content of the fields presented by either the most abstract form **1300** and the certificate view **1304**. A combination certificate could provide links to other certificates with further related information and access roles and permissions required to access those links. A combination certificate may also contain a chain of custody and a timeline. In some embodiments, a consumer or third party **1058** can verify an intermediate abstract form of a combination certificate **1080** with a verification authority **1060**. In such a case the consumer can send a loose query (for example, "has the student graduated before 2004?", "is a student's GPA above 3.0?", "is an asset owned is valued above $2M?"). The verification authority or a server employed by the verification authority then interprets the queries and translates such loose queries into elaborate lower level queries resulting in partial or exact matches. This ability to interpret user queries or verification requests from a subset of fields in a combination certificate and translating such loose, high level or abstract queries into precise, elaborate and lower level queries makes it easier to verify certain certificates without requiring precise information or queries.

Referring to FIG. **23**, and additionally referring to FIGS. **9** and **10**, the process for issuing and verifying certificates for multiple documents or objects on multiple blockchains linked to the same user, according to an embodiment of the present invention is described in more detail. The user registration process **1624** needs to be done only once for a user **1052**, generating a seal contract **1600**. Similarly, the certification process **1622/1624** is done once for the user generating a certification contract **1602**. The seal and certification contracts **1600**, **1602** are deployed on a blockchain network **1654**. The user **1052** is the owner or custodian of a documents or objects **1050** and **1051** for which combination certificates **1080** and **1081**, as described above and shown in FIG. **17**, are issued by separate issuers **1054** and **1055** on separate blockchain networks **1056** and **1057** respectively. While issuing the certificate for documents/objects **1050** and **1051**, the respective issuers **1054** and **1055** verify the user identity from the certification contract **1602** deployed on the blockchain network **1654**. The user **1052** can maintain the same identity across multiple blockchain networks (such as **1056** and **1057**) for getting the digital certificates for multiple documents/objects (such as **1050** and **1051**) without going through the user registration and certification process again. The user **1052** can share the combination certificates **1080** and **1081** with a consumer or third party **1058**. The consumer or third party **1058** can get the combination certificates **1080** and **1081** verified from the verification authority **1060**. To verify a certificate, the verification authority looks up the certificate on the corresponding blockchain network and then performs the verification steps described hereinabove.

FIG. **24** is an illustration of a sequential model of document/object existence where the derived forms of a document/object are recorded on multiple blockchains, according to an embodiment of the invention. A document or object **1280** can be processed, edited or modified to create multiple derived objects **1282** and **1284** which exist sequentially (as in the case of Diamonds). The combined existence, ownership, custody and integrity of a document or object **1280** is recorded in a combination certificate **1360** on a blockchain network **1292** and owned by a first user **1286**. Similarly, the derived objects can be processed/recorded as subsequent second and third combination certificates **1362**, **1364** in a successive sequence of second and third blockchain networks **1294** and **1296**, sequentially, and owned by successive second and third users **1286**, **1290**, respectively. In the sequential case, the document/object gets transformed into another document/object and recorded on the next blockchain but is not present in the previous one. The sequential model is a lifetime trajectory where an object can pass through (or get recorded in) multiple blockchains but is active in only one, and leaves a trail. A timeline of existence, ownership, custody and integrity **1372** can be established for an object **1280** where each point in the timeline **1366**, **1368**, **1370** corresponds to the original or derived forms of a document/object and is associated with each of the first, second, and third blockchain networks **1292**, **1294**, **1296** as well as the first, second, and third users **1286**, **1288**, **1290**.

FIG. **25** is an illustration of a concurrent model of document/object existence where the derived forms of a document/object are recorded on multiple blockchains, according to an embodiment of the invention. A document or object **1336** can be processed, edited or modified to create multiple derived objects **1338** and **1340** which exist concurrently (as in prescription and retail and payment blockchains). The combined existence, ownership, custody and integrity of a document or object **1336** is recorded in a combination certificate **1348** on a blockchain network **1342** and owned by a first user **1330**. Similarly, the derived objects can be processed/recorded in second and third combination certificates **1350**, **1352** in a successive sequence of blockchain networks **1334**, **1346**, concurrently, and owned by second and third users **1332**, **1334**, respectively. In the concurrent model the document/object can exist in derived forms in multiple chains.

Some of the illustrative aspects of the present invention may be advantageous in solving the problems herein described and other problems not discussed which are discoverable by a skilled artisan.

While the above description contains much specificity, these should not be construed as limitations on the scope of any embodiment, but as exemplifications of the presented embodiments thereof. Many other ramifications and variations are possible within the teachings of the various embodiments. While the invention has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made, and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best or only mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims. Also, in the drawings and the description, there have been disclosed exemplary embodiments of the invention and, although specific terms may have been employed, they are unless otherwise stated used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention therefore not being so limited. Moreover, the use of the terms first, second, etc. do not denote any order or importance, but rather the terms first, second, etc. are used to distinguish one element from another. Furthermore, the use of the terms a, an, etc. do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item.

Thus the scope of the invention should be determined by the appended claims and their legal equivalents, and not by the examples given.

That which is claimed is:

1. A method of issuing blockchain-based digital certificates comprising:

receiving from a user hashed user identification information and object information;

recording to a digital certificate smart contract deployed at a digital certificate smart contract address on a blockchain network the hashed user identification information and object information and a timestamp of when the hashed user identification information and the object information were received, defined as a received timestamp;

signing the digital certificate smart contract with an issuer signature;

performing a user identity verification process to confirm a user identity, the user identity verification process comprising:

receiving from the user a user certification record address, hashed user identification information that has been signed with a private key of the user defined as received user identification information, hashed object information defined as received object information, and a user public key;

obtaining each of a sealed user record address, a sealed verification record, and a token from a user certification record at the user certification record address;

retrieving hashed user identification information from a sealed user record at the sealed user record address, defining retrieved user identification information;

decrypting the received user identification information using the user public key, defining decrypted user identification information;

comparing the decrypted user identification information with the retrieved user identification information;

retrieving a hashed verification record from a sealed verification record at the sealed verification record address, defining a retrieved verification record;

determining if the token from the user certification record address is valid;

upon determining the token from the user certification record address is valid, generating a generated verification record comprising the retrieved user identification information and the token;

generating a hashed verification record by applying a hash function to the generated verification record;

comparing the hashed verification record with the retrieved verification record; and

confirming the user identity by determining the decrypted user identification information and the retrieved user identification information are at least a partial match and the hashed verification record and the retrieved verification record are at least a partial match; and

upon confirming the user identity, generating a combination certificate configured to verify the user's ownership of an object associated with the object information.

2. The method of claim 1 wherein the object information is derived from a digital object comprising content; and wherein the object information comprises a unique identifier generated by applying a cryptographic hash function to the content of the digital object.

3. The method of claim 1 wherein the object information is derived from a physical object comprising an object identifier; and wherein the object information comprise a unique identifier generated by applying a cryptographic hash to the object identifier of the physical object.

4. The method of claim 1 wherein the object identifier is an inscription on the physical object.

5. The method of claim 1 further comprising:

receiving a combination certificate from a consumer, defining a received combination certificate;

performing a combination certificate verification process on the received combination certificate to verify the received combination certificate; and

upon verifying the received combination certificate, sending a confirmation verification response to the consumer.

6. The method of claim 5 further comprising:

generating a combination certificate hash value by applying a hash function to the received combination certificate; and

recording the combination certificate hash value to the digital certificate smart contract;

wherein the combination certificate verification process comprises:

identifying a signature of the received combination certificate;

obtaining a received digital certificate smart contract address from the received combination certificate;

generating a query hash value by applying a hash function to the received combination certificate;

looking up the combination certificate on the digital certificate smart contract at the digital certificate smart contract address;

verifying the query hash value matches a combination certificate hash value comprised by the digital certificate smart contract;

verifying the signature of the combination certificate matches the issuer signature of the digital certificate smart contract; and

verifying the combination certificate is valid and active.

7. The method of claim 5 further comprising:

receiving from the user a digital certificate smart contract address, hashed user identification information signed by a private key of the user, and hashed object information;

obtaining a user certification record address from a digital certificate smart contract at the digital certificate smart contract address;

obtaining a sealed user record address, a sealed verification record address, and a token from a user certification record at the user certification record address;

retrieving hashed user identification information, defined as retrieved user identification information, from a sealed user record at the sealed user record address;

decrypting the received user identification information using the user's public key, defining decrypted user identification information;

comparing the decrypted user identification information with the retrieved user identification information;

retrieving a hashed verification record from a sealed verification record at the sealed verification record address;

determining if the token from the user certification record address is valid;

generating a generated verification record comprising the retrieved user identification information and the token;

generating a hashed generated verification record by applying a hash function to the generated verification record; and

comparing the hashed generated verification record to the hashed verification record;

retrieving object information, defining retrieved object information, from the digital certificate at the digital certificate address;

comparing the retrieved object information with the hashed object information;

retrieving from the digital certificate smart contract a timestamp, defining a retrieved timestamp; and

upon determining the decrypted user identification information with the retrieved user identification information are at least a partial match, the hashed generated verification record to the hashed verification record are at least a partial match, and the retrieved object information and the hashed object information are at least a partial match, sending to the user the retrieved user identification information, the retrieved object information, and the retrieved timestamp.

8. The method of claim 1 wherein generating the combination certificate comprises:

generating a combination certificate comprising the user's certification record address, the received object information, and the received timestamp;

generating a combination certificate hash value from a hash function including the combination certificate as an input;

encrypting the combination certificate hash value with an issuer private key, defining an issuer signature;

signing the combination certificate with the issuer signature, defining a signed combination certificate; and

recording the signed combination certificate to the digital certificate smart contract.

9. The method of claim 1 further comprising:

receiving hashed second user identification information associated with a second user and a derivative of the object information, defining a derivative object information;

recording to a second digital certificate smart contract deployed at a second digital certificate smart contract address on a second blockchain network the hashed second user identification information and the derivative object information and a timestamp of when the hashed second user identification information and the derivative object information were received, defined as a received timestamp;

signing the second digital certificate smart contract with a second issuer signature;

generating a second combination certificate configured to verify the second user's ownership of a derivative object associated with the derivative object information; and sending the second combination certificate to the second user.

10. The method of claim **9** wherein the object information is derived from a digital object comprising content; wherein the derivative object is a digital object comprising a subset of the content of the digital object from which the digital object is derived; and wherein the derivative object information comprises a unique identifier generated by applying a cryptographic hash function to the derivative object.

11. The method of claim **9** further comprising:

receiving hashed third user identification information associated with a third user and the derivative object information;

recording to a third digital certificate smart contract deployed at a third digital certificate smart contract address on a third blockchain network the hashed third user identification information and the derivative object information and a timestamp of when the hashed third user identification information and the derivative object information were received, defined as a received timestamp;

signing the third digital certificate smart contract with a third issuer signature;

generating a third combination certificate configured to verify the third user's ownership of a derivative object associated with the derivative object information;

sending the third combination certificate to the third user; and

recording to the second digital certificate smart contract an indication that the second digital certificate smart contract is expired.

12. The method of claim **9** further comprising:

receiving hashed third user identification information associated with a third user and a second derivative of the object information, defining a second derivative object information;

recording to a third digital certificate smart contract deployed at a third digital certificate smart contract address on a third blockchain network the hashed third user identification information and the second derivative object information and a timestamp of when the hashed third user identification information and the second derivative object information were received, defined as a received timestamp;

signing the third digital certificate smart contract with a third issuer signature;

generating a third combination certificate configured to verify the third user's ownership of a derivative object associated with the second derivative object information; and

sending the third combination certificate to the third user;

wherein the second derivative object information exists concurrently with the derivative object information.

13. The method of claim **1** further comprising:

generating a secondary combination certificate configured to verify the user's ownership of a subset of information object associated with the object information; and

sending the secondary combination certificate to a second user.

14. The method of claim **13** further comprising:

receiving a secondary combination certificate from a consumer, defining a received combination certificate;

performing a combination certificate verification process on the received combination certificate to verify the received combination certificate;

upon verifying the received combination certificate, sending a confirmation verification response to the consumer; and

sending a subset of information comprised by the object information to the consumer.

15. The method of claim **1** further comprising recording to the digital certificate smart contract a location of the user when the user identification information and the object information were received.

16. The method of claim **1** wherein the blockchain network supports at least one decentralized consensus protocols of proof-of-work proof-of-stake, proof-of-activity, proof-of-burn, proof-of-capacity, and proof-of-elapsed time.

17. A system for issuing blockchain-based digital certificates comprising:

a processor;

a data store positioned in communication with the processor; and

a network communication device positioned in communication with each of the processor, the data store, and a network;

wherein the network communication device is operable to receive from a user hashed user identification information, object information, and a user public key;

wherein the processor is operable to record to a digital certificate smart contract deployed at a digital certificate smart contract address on a blockchain network the hashed user identification information and object information and a timestamp of when the hashed user identification information and the object information were received, defined as a received timestamp;

wherein the processor is operable to sign the digital certificate smart contract with an issuer signature; and

wherein the system is operable to perform a user identity verification process to confirm a user identity, comprising:

the network communication device obtaining each of a sealed user record address, a sealed verification record address, and a token from a user certification record at a user certification record address;

the network communication device retrieving hashed user identification information from a sealed user record at the sealed user record address, defining retrieved user identification information;

the processor decrypting the received user identification information using the user public key, defining decrypted user identification information;

the processor comparing the decrypted user identification information with the retrieved user identification information;

the network communication device retrieving a hashed verification record from a sealed verification record at the sealed verification record address, defining a retrieved verification record;

the processor determining if the token from the user certification record address is valid;

upon determining the token from the user certification record address is valid, the processor generating a generated verification record comprising the retrieved user identification information and the token;

the processor generating a hashed verification record by applying a hash function to the generated verification record;

the processor comparing the hashed verification record with the retrieved verification record;

the processor confirming a user identity by determining the decrypted user identification information and the retrieved user identification information are at least a partial match and the hashed verification record and the retrieved verification record are at least a partial match; and

upon confirming the user identity, the processer generating a combination certificate configured to verify the user's ownership of an object associated with the object information.

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