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(54) **SYSTEM AND METHOD OF NON-CENTRALIZED ZERO KNOWLEDGE AUTHENTICATION FOR A COMPUTER NETWORK**

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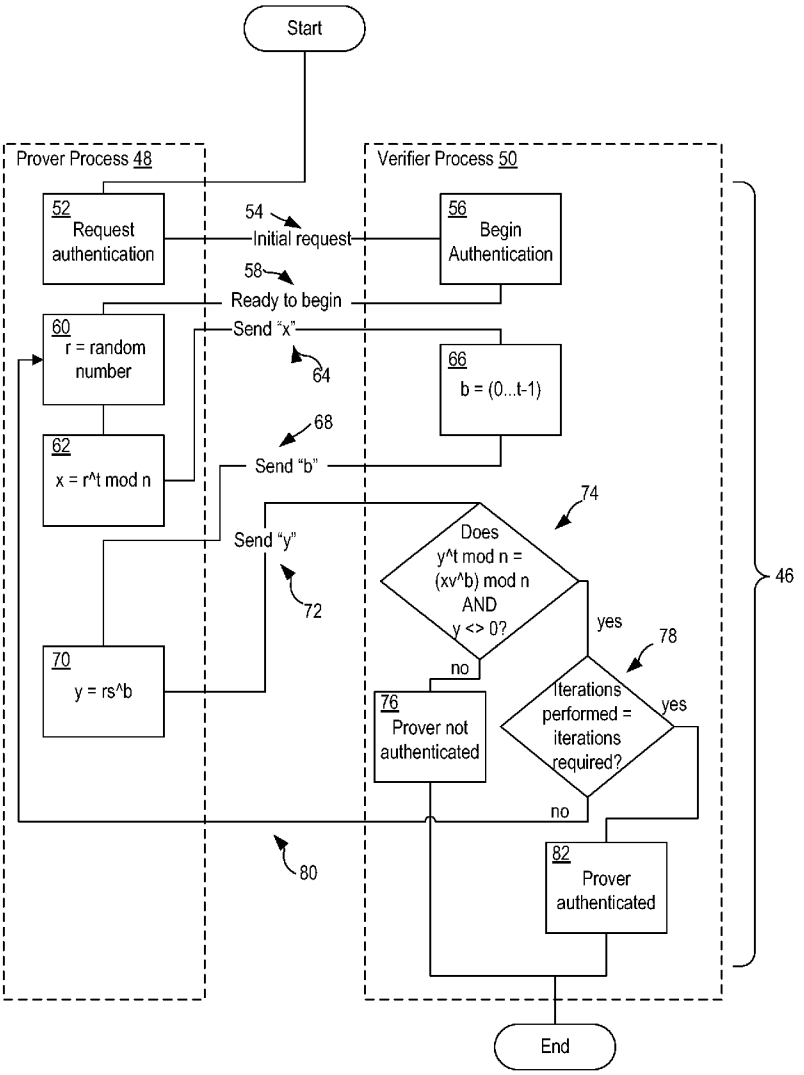
(57) **ABSTRACT**

Zero-knowledge authentication proves identity without revealing information about a secret that is used to prove that identity. An authentication agent performs authentication of a prover agent without knowledge or transfer of the secret. A non-centralized zero-knowledge authentication system contains multiple authentication agents, for access by multiple computers seeking access on a computer network through local prover agents. Once authenticated, those multiple computers may also implement authentication agents. The secret may periodically expire by publishing a new encrypted secret by a trusted source, thwarting attempts to factor or guess information about the secret.



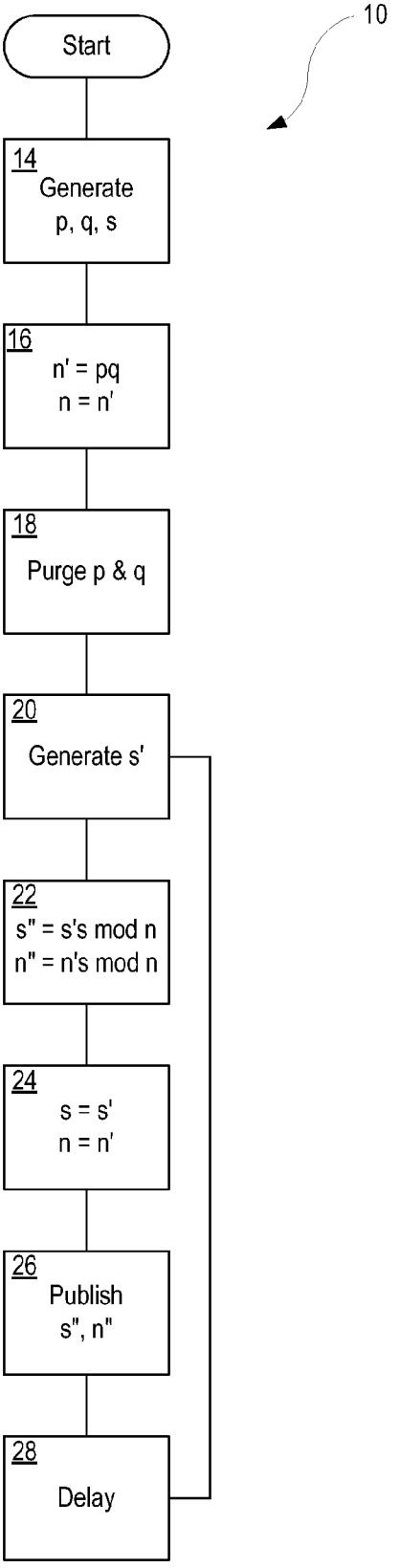

10
Start
14
Generate
p, q, s
16
n' = pq
n = n'
18
Purge p & q
20
Generate s'
22
s" = s's mod n
n" = n's mod n
24
s = s'
n = n'
26
Publish
s", n"
28
Delay

FIG. 1

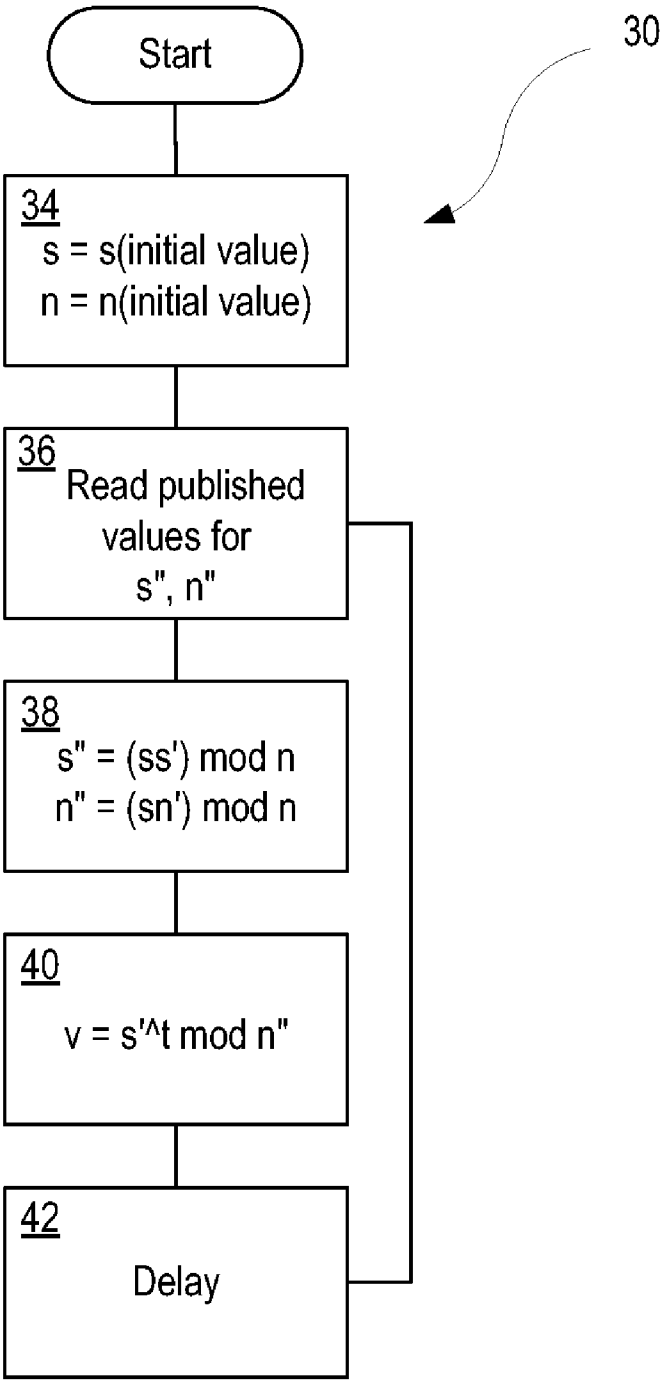

Start
30
34
s = s(initial value)
n = n(initial value)
36
Read published values for s", n"
38
s" = (ss') mod n
n" = (sn') mod n
40
v = s'^t mod n"
42
Delay

FIG. 2

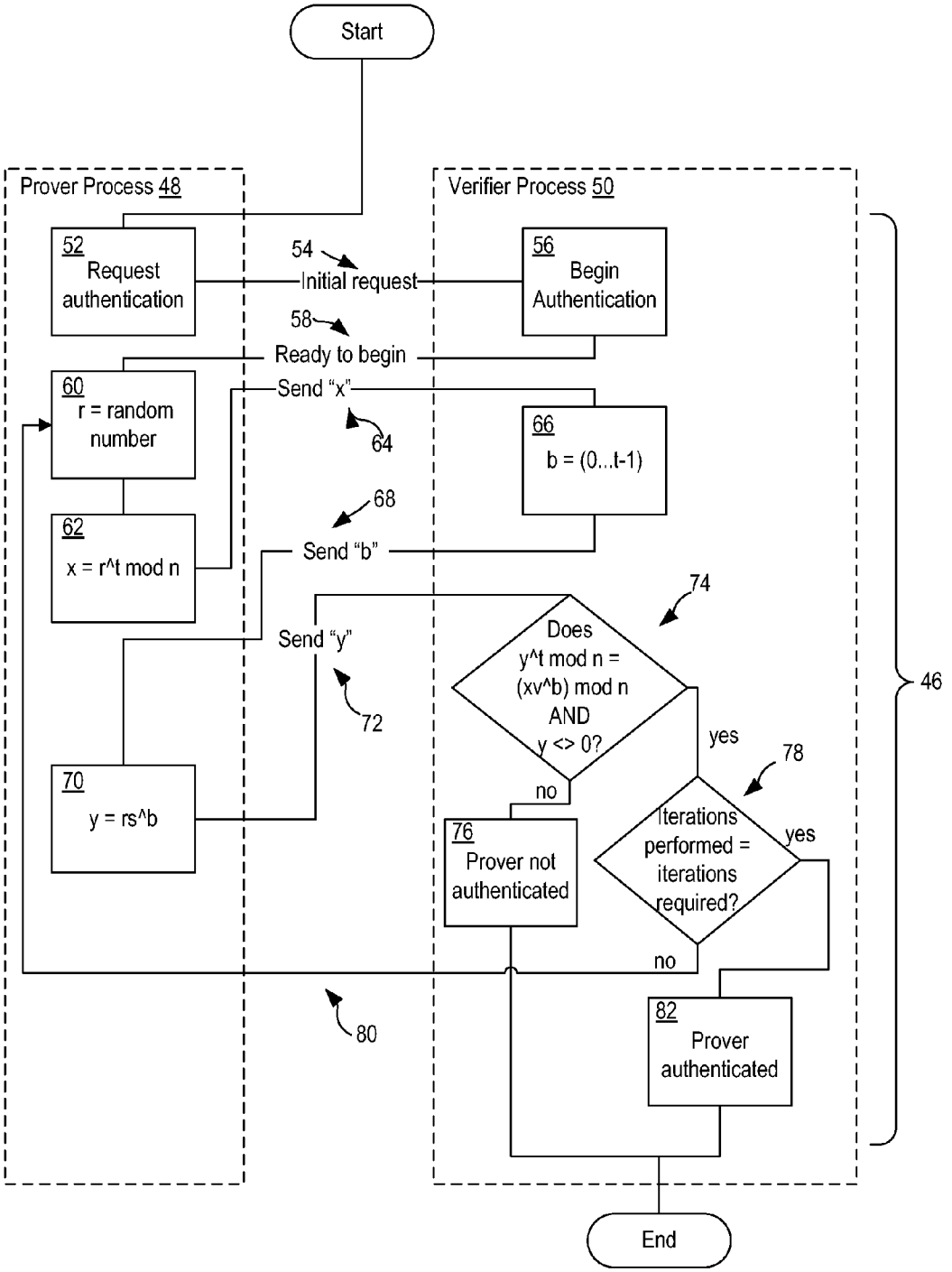

Start
Prover Process 48
Verifier Process 50
52
Request authentication
54
Initial request
56
Begin Authentication
58
Ready to begin
60
r = random number
Send "x"
64
66
b = (0...t-1)
62
x = r^t mod n
68
Send "b"
74
Send "y"
72
Does y^t mod n = (xv^b) mod n AND y <> 0?
yes
78
70
y = rs^b
no
76
Prover not authenticated
Iterations performed = iterations required?
yes
no
80
82
Prover authenticated
46
End

FIG. 3

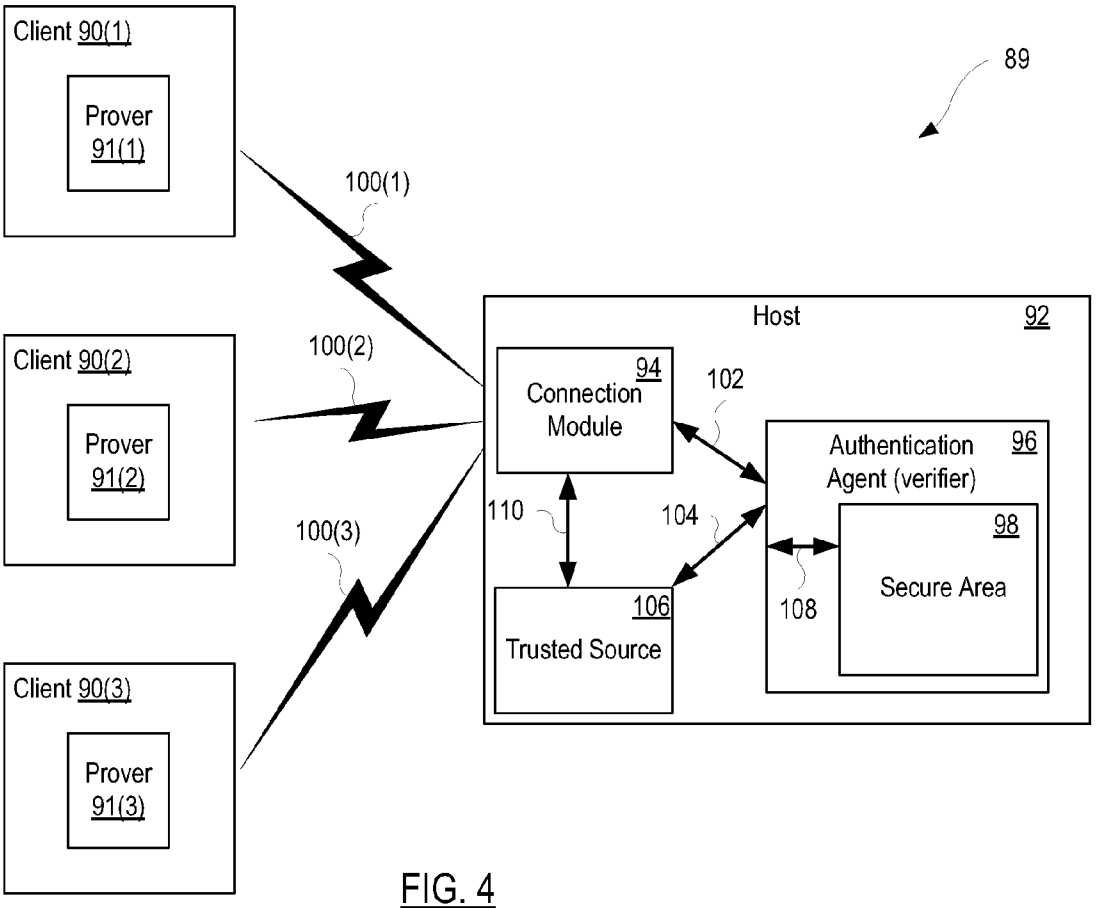

Client 90(1)
Prover 91(1)
Client 90(2)
Prover 91(2)
Client 90(3)
Prover 91(3)
89
100(1)
100(2)
100(3)
Host 92
94 Connection Module
102
Authentication Agent (verifier) 96
110
104
98 Secure Area
108
106 Trusted Source

FIG. 4

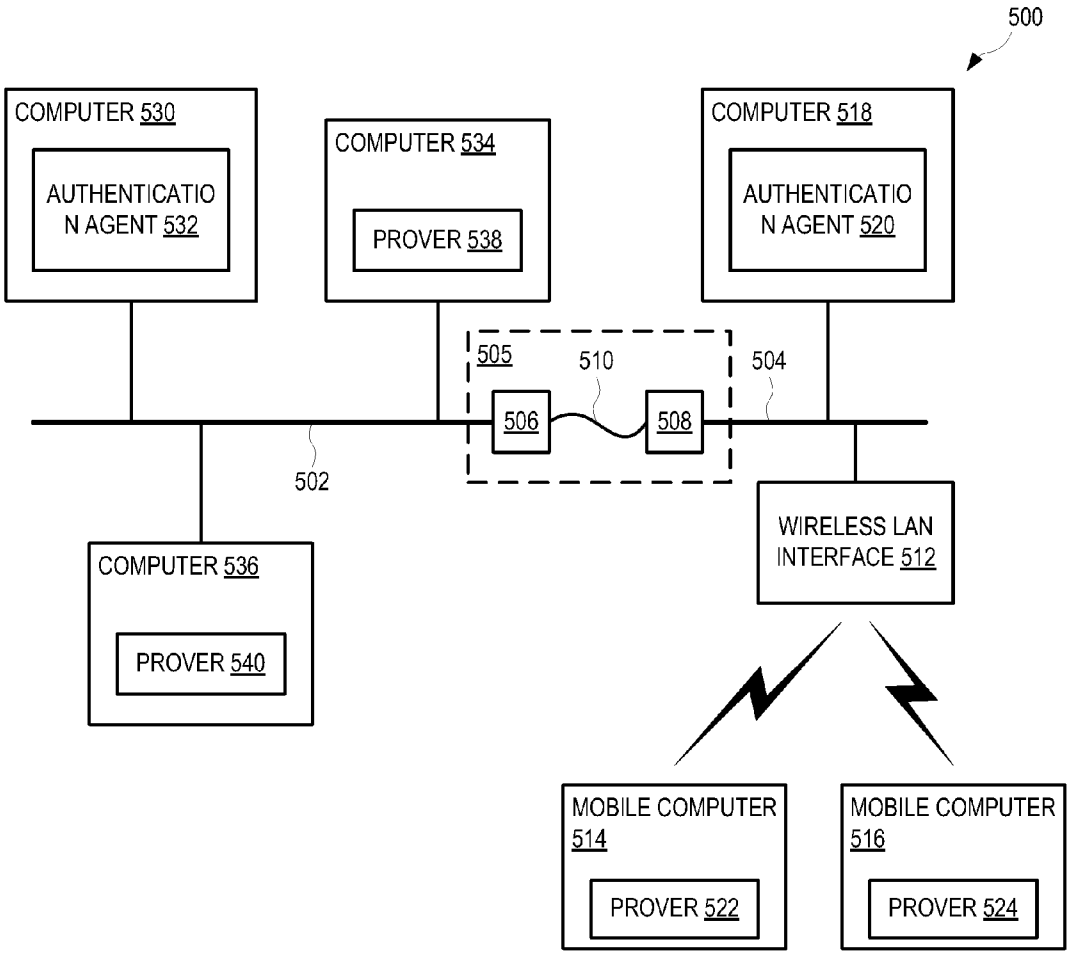

500
COMPUTER 530
AUTHENTICATIO N AGENT 532
COMPUTER 534
PROVER 538
COMPUTER 518
AUTHENTICATIO N AGENT 520
505
510
504
506
508
502
COMPUTER 536
PROVER 540
WIRELESS LAN INTERFACE 512
MOBILE COMPUTER 514
PROVER 522
MOBILE COMPUTER 516
PROVER 524

FIG. 5

SYSTEM AND METHOD OF NON-CENTRALIZED ZERO KNOWLEDGE AUTHENTICATION FOR A COMPUTER NETWORK

RELATED APPLICATIONS

[0001] This application is a continuation of U.S. application Ser. No. 10/687,320, filed Oct. 16, 2003, which claims priority to U.S. Provisional Application No. 60/418,889, both of which are incorporated herein by reference.

BACKGROUND

[0002] Computer systems intercommunicate via computer networks. For example, a first computer system frequently communicates with a second computer system over a computer network to obtain information. The computer network may include many different communication media. In one example, the computer network is an Ethernet local area network ("LAN"). In another example, the computer network is a wireless LAN. Information stored on the first computer system is often sensitive such that access to the information must be restricted. Accordingly, the first computer system often requires that the second computer system be authenticated before allowing the second computer system to access the information. Access to the computer network may also be restricted, requiring any computer system wishing to join the computer network to be authenticated before communicating with other devices on the network.

[0003] Authentication typically utilizes an identification protocol that requires a computer system to identify itself with authority to access a restricted computer system. In one example, a first computer system may require a "password" from the second computer system to enable authentication. However, in situations where the communication between the first and second computer systems is monitored by a third computer system, the password may be obtained by the third computer system, allowing unauthorized access by the third computer system to the first computer system. Identification protocols that provide authentication without transmission of a secret password, known as a 'key', are therefore utilized. A zero-knowledge identification protocol ("ZKIP") is one example of a protocol that provides authentication without transmitting the key, thereby preventing the key from being stolen and misused.

[0004] Typically, in a computer network that uses authentication, there is only one authenticator that stores keys used to authenticate requests from other computer systems. The use of a single authenticator, however, may result in access problems when the computer system running the authenticator fails, or where communications to the authenticator fail, for example. Where the authentication is for important data or services, failure of the authenticator may prevent access to the data or services. Further, the use of a single authenticator also causes congestion within the computer network as all authentication traffic is directed to a single location.

[0005] Where a computer network is highly scalable and dynamic it is important to authenticate each computer system as it attempts to access the computer network. A digital mobile telephone network is one example of a dynamic computer network. The digital mobile telephone network consists of multiple base stations that are networked together, each base station providing one or more cells for the digital telephone network. Each mobile telephone handset connects to, and disconnects from, these cells as the handset changes location. It is therefore important that any authentication process used within the cell network be as fast and efficient as possible. Typically, to meet speed requirements for a digital mobile telephone network, the authentication process is simplified, thereby making it less reliable and less secure, making the mobile telephone network highly susceptible to snooping by third parties.

SUMMARY OF INVENTION

[0006] U.S. Pat. No. 4,748,668, titled Method, Apparatus and Article for Identification and Signature, is incorporated herein by reference.

[0007] In one aspect, a method provides non-centralized zero knowledge authentication within a dynamic computer network. The dynamic computer network includes two or more authentication agents that interact with prover agents within computers wishing to gain access to the computer network. Using a zero-knowledge authentication protocol, the prover is either authenticated, or not, without communication of a secret.

[0008] In another aspect, a software product (firmware, for example) is distributed with a hardware device to provide non-centralized zero-knowledge authentication. In one example, the hardware device is a router connected to a network. The router communicates with a prover agent within a mobile computer (e.g., a laptop computer system or a mobile telephone handset) that seeks access to the network. Once the prover agent is authenticated and authorized, the router permits the mobile computer to access part of or the entire network.

[0009] In one aspect, methods are provided for authentication of identity or group membership. One such method involves zero-knowledge authentication. An authentication dialog between a verifying agent ("verifier") and an agent to be verified ("prover") is conducted without revealing information about a secret ("secret") that is used to prove identity (or group membership without actually disclosing prover's identity). Authentication is achieved when verifier asks prover I-times (I>0) to perform an action that can only be reliably performed by an entity that knows a secret. Prover answers verifier with results of action. If prover does not answer correctly, authentication is invalid. This challenge-response-validation iteration is repeated I-times to establish a sufficient level of probability that prover answered with knowledge of secret. One advantage of zero-knowledge authentication is inability for an eavesdropper to learn secret and steal means to prove identity to verifier. Another advantage is inability for verifier to later masquerade as a prover to a third-party.

[0010] In another aspect, methods are provided to allow for greater probability of correctly authenticating prover with fewer challenge-response-validation iterations. One such method allows prover to have a set, greater than two, of possible answers, as is provided by Fiat-Shamir protocol. For example, a prover that answers verifier correctly with a member of set {0, 1, 2, 3} has a 25% chance of being incorrectly authenticated with one challenge-response-validation iteration. Following Fiat-Shamir protocol, prover will answer verifier with one of two possible answers {0, 1} and thereby require two challenge-response-validation iterations to achieve the same level of authentication probability.

[0011] In another aspect, an authenticator agent require a prover agent to repeat an authentication protocol until a speci-

fied confidence level that a prover agent is correctly authenticated has been satisfied. For example, a confidence level of 99% may require 10 iterations, where a confidence level of 99.9999% may require 20 iterations.

[0012] In another aspect, a method of protecting a host from unauthorized client access over a network includes the steps of: creating a prover agent application on the client; creating a verifier agent application on the host; and creating a trusted source application to generate and publish encrypted values of a secret and product of first and second large prime numbers. The encrypted values are read for the secret and product, by the provider and verifier from the trusted source. The secret is decrypted, by the prover and verifier, and the product is decrypted, by the prover and verifier. A plurality of verification dialog is performed between the prover and verifier, wherein the prover demonstrates knowledge of the secret and product without exposing the values of the secret and product. The client is denied access when the prover fails to demonstrate knowledge of the secret and product, and granted access when the client succeeds in demonstrating knowledge of the secret and product.

[0013] In another aspect, methods are provided to validate agents without unique indicia. One such method allows agents to validate based on indicia that they are within a category of agents who have knowledge of secret common to all authentic agents. An advantage of using non-unique indicia is elimination of overhead required to generate, maintain, and validate unique indicia

[0014] In another aspect, methods are provided to publish secret used to authenticate agents. One such method allows a trusted source to periodically update and publish the secret and product of two large prime numbers ("product"). The frequency of updates is less than the predicted length of time a malicious party could factor product or guess secret. Trusted source generates, encrypts, and publishes secret and product. Prover and verifier read encrypted values for secret and product, from trusted source, and use previous values of secret and product to decrypt new values for secret and product. Prover and verifier now have all information required to perform authentication processes.

[0015] One advantage of using methods described above is elimination of steps required to derive keys to encrypt and decrypt messages.

BRIEF DESCRIPTION OF DRAWINGS

[0016] FIG. **1** is a flowchart illustrating one process for generating and publishing secret and product of two large prime numbers;

[0017] FIG. **2** shows a method of decrypting secret and product of two large prime numbers;

[0018] FIG. **3** shows a challenge-response-validation iteration process between prover and verifier agent; and

[0019] FIG. **4** shows a system with three clients, each including a prover agent, and a host computer with a verifier agent.

[0020] FIG. **5** illustrates one system for providing non-centralized zero knowledge authentication within a dynamic computer network.

DETAILED DESCRIPTION OF DRAWINGS

[0021] FIG. **1** shows one method **10** for generating and publishing a secret and a product of two large prime numbers. Method **10** is, for example, implemented by a 'trusted' source as described below. In step **14**, an initial value of secret s is generated from a seed value, and two large prime numbers ("p" and "q") are randomly generated. Step **16** calculates a current product n' (n-prime) of the two large prime numbers p and q, and initializes previous product value n (n-not prime) as equal to n'. In step **18**, p and q are purged and made unreadable. In step **20**, current secret number s' (s-prime) is generated to be a value relatively prime to n, greater than **0**, and less than n. In step **22**, values for encrypted secret s" (s-double prime) and encrypted product of two large numbers n" (n-double prime) are generated as: s"=s's mod n, and n"=n's mod n. In step **24**, previous secret number s (s-not prime) is set equal to s' and n is set equal to n'. In step **26**, values for n" and s" are published. At this point, publication process is complete and process **10** waits in step **28**.

[0022] Values for s" and n" may become compromised by a malicious party that is able to factor or guess values. Therefore, the delay in step **28** terminates before values are likely to be compromised and process **10** is restarted at step **20** where a new s' is generated.

[0023] FIG. **2** shows one method **30** of decrypting secret s" and product n". In step **34**, an agent (e.g., a prover agent or an authentication agent) is created with an initial value for s and n. In step **36**, the agent reads values of s" and n" published by the trusted source (e.g., method **10**, FIG. **1**). In step **38**, values of s" and n" are decrypted by a modulus inverse operation. In step **40**, the size of answer set ("t") is used to determine a value ("v") calculated as result of s'^t mod n".

[0024] At this point, prover and verifier agents have data required to perform authentication. Because values for s" and n" published by trusted source periodically change, updated values for s" and n" will be retrieved. Step **42** is a delay based on a specific length of time or may be triggered at the start of an authentication process (e.g., a zero-knowledge identification protocol). After the delay in step **42**, method **30** continues with step **36** and the agent will again contact the trusted source and read new values for s" and n".

[0025] FIG. **3** shows a challenge-response-validation iteration dialog between a prover agent (shown as process **48**) and a verifier agent (shown as process **50**). Process **48** performs processing to establish a need to authenticate and begins zero-knowledge identification protocol **46** in step **52**, which may include retrieving and decrypting current values of secret s" and the product n". In step **52**, process **48** (prover) sends a signal **54** to process **50** (verifier) to begin zero-knowledge identification protocol **46**. In step **56**, process **50** (verifier) performs any initial processing, which may include retrieving and decrypting current values of secret s" and product n". in step **56**, process **50** sends signal **58** to process **48** (prover) to begin the authorization process. In step **60**, process **48** (prover) generates a random number ("r"). Random number r is then used, in step **62**, to generate a number x such that x=r^t mod n. In step **62**, process **48** sends a signal **64** containing x to process **50** (verifier). In step **66**, process **50** (verifier) then calculates a reply value b as a member of set $\{0 \ldots t-1\}$. In step **66**, process **50** sends a signal **68** containing b to process **48** (prover). In step **70**, process **48** (prover) uses b to calculate a number y such that y=rs^b. In step **70**, process **48** sends a signal **72** containing y to process **50** (verifier). Step **74** in process **50** is a decision. In step **74**, process **50** performs a test to determine if process **48** (prover) has passed this iteration of zero-knowledge identification protocol **46**. If y^t mod n=(xv^b) mod n and y<>0, then process **50** continues with step **78**; otherwise process **50** continues with step **76**. Step **78**

in process **50** is a decision. In step **78**, the number of challenge-response-verification iterations is compared to the number of iterations required to establish a suitable probability of correct authentication. If the number of challenge-response-validation iterations performed is the same as the number of challenge-response-validation iterations required, and process **48** (prover) has not failed any iterations, then process **48** continues with step **82**; otherwise process **50** sends a signal **80** to process **48** to continue with step **60**, thus beginning another challenge-response-validation iteration by repeating steps **60** through **74**.

[0026] In step **82**, process **50** continues with processing appropriate for authenticated process **48** (prover) and process **50** terminates. In step **76**, process **50** (verifier) continues processing as appropriate for non-authentic agents, and process **50** terminates.

[0027] FIG. **4** shows a system **89** with three clients **90**(**1**-**3**), each running a prover agent **91**(**1**-**3**), and a host **92** running an authentication agent **96** (verifier). Prover agents **91**(**1**-**3**) implement process **48**, FIG. **3**, for example. Authentication agent **96** implements process **50**, FIG. **3**, for example. Communication links **100**(**1**-**3**) establishes connectivity between clients **90**(**1**-**3**) and a connection module **94** within host **92**. In system **89**, client **90**(**1**) seeks access to secure area **98** of host **92**. Communication link **100**(**1**) establishes connectivity between client **90**(**1**) and connection module **94** within host **92**. In one example, communication link **100**(**1**) is a telephone dial-up connection. In another example, communication link **100**(**2**) is an Internet connection. In another example, authentication agent **96** (verifier) protects secure area **98** allowing access only to authenticated clients. Communication link **100** (**3**) is an Ethernet LAN connection. After client **90**(**1**) is authenticated by host (**92**), a connection **102** is established and client **90**(**1**) is allowed access to secure area **98**. Once this connection has been established, authentication agent **96** may distribute a new secret from trusted source **106** to prover agent **90**(**1**) for use in future authentication dialog. When prover agent **90**(**1**) requests authentication at a future time after connection **110** has been broken, authentication agent **96** requests credentials from prover agent **90**(**1**) from trusted source **106** via the hosts internal connection **104**. At this point the authentication dialog may take place between client **90**(**1**) and host **92** to reestablish a trusted connection.

[0028] Zero-knowledge identification protocol **46**, FIG. **3**, is then performed. If zero-knowledge identification protocol **46** is successful, an access link **108** is activated to secure area **98**, and client **90**(**1**) may proceed with further processing. If zero-knowledge identification protocol **46** is not successful, processing continues with knowledge that client **90**(**1**) is not authorized and, at a minimum, client **90**(**1**) is inhibited from access to secure area **98**.

[0029] FIG. **5** shows one system **500** that provides non-centralized zero-knowledge authentication within a dynamic network. Illustratively, system **500** includes two Ethernet LANs **502** and **504** that are not co-located. LAN **502** is connected to LAN **504** via a communication apparatus **505** that contains connection units **506**, **508** and a communication link **510**. Connection units **506** and **508** are, for example, routers or microwave transceivers. Communication link **510** is, for example, an ISDN link, the Internet, or a microwave link that provides data communication between two remote locations.

[0030] LAN **504** is shown connected to a wireless LAN device **512** that provides wireless connectivity to mobile computers **514** and **516**. LAN **504** also illustratively connects to computer system **518** that includes authentication agent **520** (verifier). Before mobile computer **514** connects to LAN **504**, it is first authenticated using zero-knowledge identification protocol **46** as shown in FIG. **3**. Mobile computer **514** includes a prover agent **522** that interacts with authentication agent **520** to perform zero-knowledge identification protocol **46**. Mobile computer **516** includes a prover agent **524** that interacts with authentication agent **520** to gain authentication to access LAN **504**.

[0031] Trusted source **106**, FIG. **4**, implements process **10**, FIG. **1**, to generate a new secret s" and a new product n" periodically to prevent the malicious party compromising the values by guessing or factoring. Thus, once computer system **536** has been authenticated and is connected to LAN **502** it receives new values for secret s" and product n", using an encrypted message based on its current values for secret s" and product n". Thus, integrity and security of system **500** is maintained at a high level. Only during initialization of system **500**, or when a mobile computer (e.g., mobile computers **514**, **516**) connects to wireless LAN interface **512** and requests authentication, is a predefined secret used.

[0032] Computer system **530** illustratively connects to LAN **502** and includes authentication agent **532** (prover). Computer systems **534** and **536** also connect to LAN **502**; computer system **534** includes a prover agent **538** and computer system **536** includes a prover agent **540**. Prover agent **538** interacts with authentication agent **532** to authenticate computer system **534** for access to LAN **502**. Similarly, prover agent **540** interacts with authentication agent **532** to authenticate computer system **536** for access to LAN **502**.

[0033] Authentication agents **520** and **532** operate independently to authenticate mobile computers **514**, **516** and desktop computers **534**, **536** for access to LANs **504** and **502**, respectively. Optionally, once a computer (e.g., computers **534**, **536** and mobile computers **514** and **516**) is authenticated and remains connected within system **500**, it may operate to authenticate other computers (i.e., may operate as an authentication agent). Further, once authenticated and connected within system **500**, the computer may operate to interact with other computers seeking authentication, enabling communication between the other computers and an authentication agent.

[0034] For example, and with reference to FIG. **5**, consider computer **518** and **530** existing on the computer network defined by LANs **502**, **504** and communications link **510** (at boot up to establish the network, computer **518**, **530** are initialized with the same secret and thus both operate with respective authentication agents, as shown). When any other computer **534**, **536**, **514**, **516** desires access to this computer network, it may do so only through zero knowledge authentication, such as zero-knowledge identification protocol **46** (i.e., the dialog between authentication agent **520** and prover agent **538**, **540**, **522**, **524**, respectively). Once authenticated on the network, the computer may be promoted to operate with an additional authentication agent so as to provide authentication to other computers desiring access to the network. Accordingly, the network is "dynamic" in that it allows additional, flexible authentications to occur and expand the network. To enable this non-centralized zero knowledge authentication, authentication software (including authentication and prover agents) may be preloaded into each computer (e.g., computers **514**, **516**, **518**, **530**, **534**, **536**).

[0035] In one example, a computer network includes multiple base stations that operate to provide a mobile telephone network. Each base station contains an authentication agent. Each mobile handset includes a prover agent that connects to the mobile telephone network. Before the mobile handset is allowed to use any services of the mobile telephone network, the authentication agent in the base station selected by the mobile handset interacts with the prover agent in the mobile handset. If the authentication agent is satisfied that the prover knows the secret, it becomes authenticated and authorized to use the mobile telephone network. By using a ZKIP, the secret is never transmitted to or from the mobile handset, and therefore not susceptible to malicious snooping.

What is claimed is:

1. A method of non-centralized zero-knowledge authentication for a computer network, comprising steps of:
- establishing a first computer having a first authentication agent and a first prover agent on the computer network;
- detecting a first authentication request over the computer network from a second computer having a second prover agent;
- authenticating the second prover agent through a zero-knowledge identification protocol; and
- promoting the second computer with a second authentication agent to perform authentication for the computer network.

2. The method of claim **1**, further comprising periodically generating and distributing a new secret to the first and second authentication agents.

3. The method of claim **1**, further comprising:
- detecting a second authentication request over the computer network from a third computer having a third prover agent;
- authenticating the third prover agent through a zero-knowledge identification protocol with the second authentication agent; and
- promoting the third computer with a third authentication agent to perform authentication for the computer network.

4. The method of claim **1**, further comprising periodically publishing encrypted numbers for the zero-knowledge identification protocol, including the steps of:
- generating first and second large prime numbers;
- calculating a product of the first and second large prime numbers;
- generating a secret to have a value relatively prime to the product, greater than zero and less than the product;
- encrypting the product;
- encrypting the secret; and
- publishing encrypted values of the secret and product.

5. A system of non-centralized zero-knowledge authentication for a computer network, comprising:
- two or more computers establishing the computer network, each of the computers containing an authentication agent, secret and prover agent; and
- a requesting computer having a prover agent, for requesting access to the computer network,
- wherein the prover agent of the requesting computer and one of the authentication agents of the two or more computers engaging in a zero-knowledge authentication protocol, and wherein the requesting computer operates with an authentication agent on the computer network when the requesting computer is authenticated through the zero-knowledge authentication protocol.

6. The system of claim **5**, further comprising a trusted source for periodically generating a new secret for the authentication agents of computers on the network.

7. The system of claim **5**, the requesting computer comprising a cell phone.

8. The system of claim **7**, wherein the cell phone is authenticated without transmitting the secret to or from the cell phone.

9. A software product comprising instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for non-centralized zero-knowledge authentication for a computer network, comprising:
- instructions for establishing a first computer having a first authentication agent and a first prover agent on the computer network;
- instructions for detecting a first authentication request over the computer network from a second computer having a second prover agent;
- instructions for authenticating the second prover agent through a zero-knowledge identification protocol; and
- instructions for promoting the second computer with a second authentication agent to perform authentication for the computer network.

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