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(54) **LIGHTWEIGHT AUTHENTICATION METHOD, SYSTEM, AND KEY EXCHANGE PROTOCOL FOR LOW-COST ELECTRONIC DEVICES**

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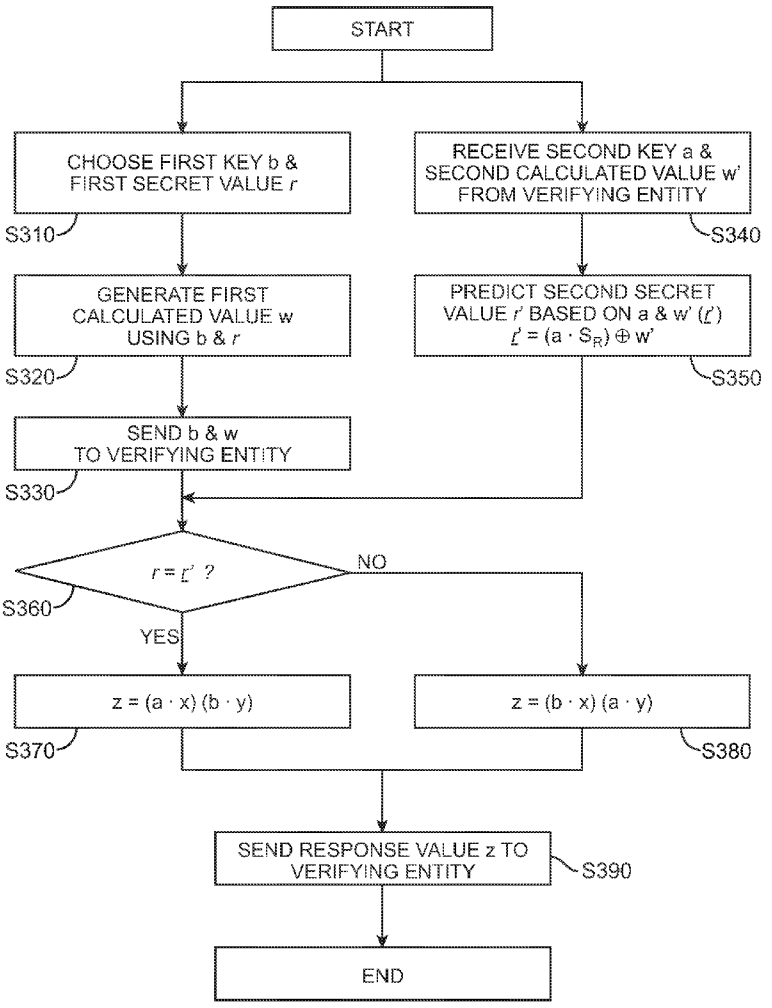
(57) **ABSTRACT**

An algorithm or an authentication system for a low-cost authenticating device such as a radio frequency identification (RFID) tag, or a sensor node are provided, by which authentication is processed efficiently without requiring complicated hardware. A claimant entity attempting to be authenticated and a verifying entity to authenticate the claimant entity, share a plurality of secret keys so that authentication is processed as the claimant entity responds to a challenge by the verifying entity. The verifying entity and the claimant entity perform authentication using Learning Parity with Noise (LPN) problem. The verifying entity and the claimant entity generate keys independently from one another, and exchange the generated keys. The claimant entity may generate an encrypted value for use in the authentication, using a basic Boolean Exclusive OR and a logical AND operations.



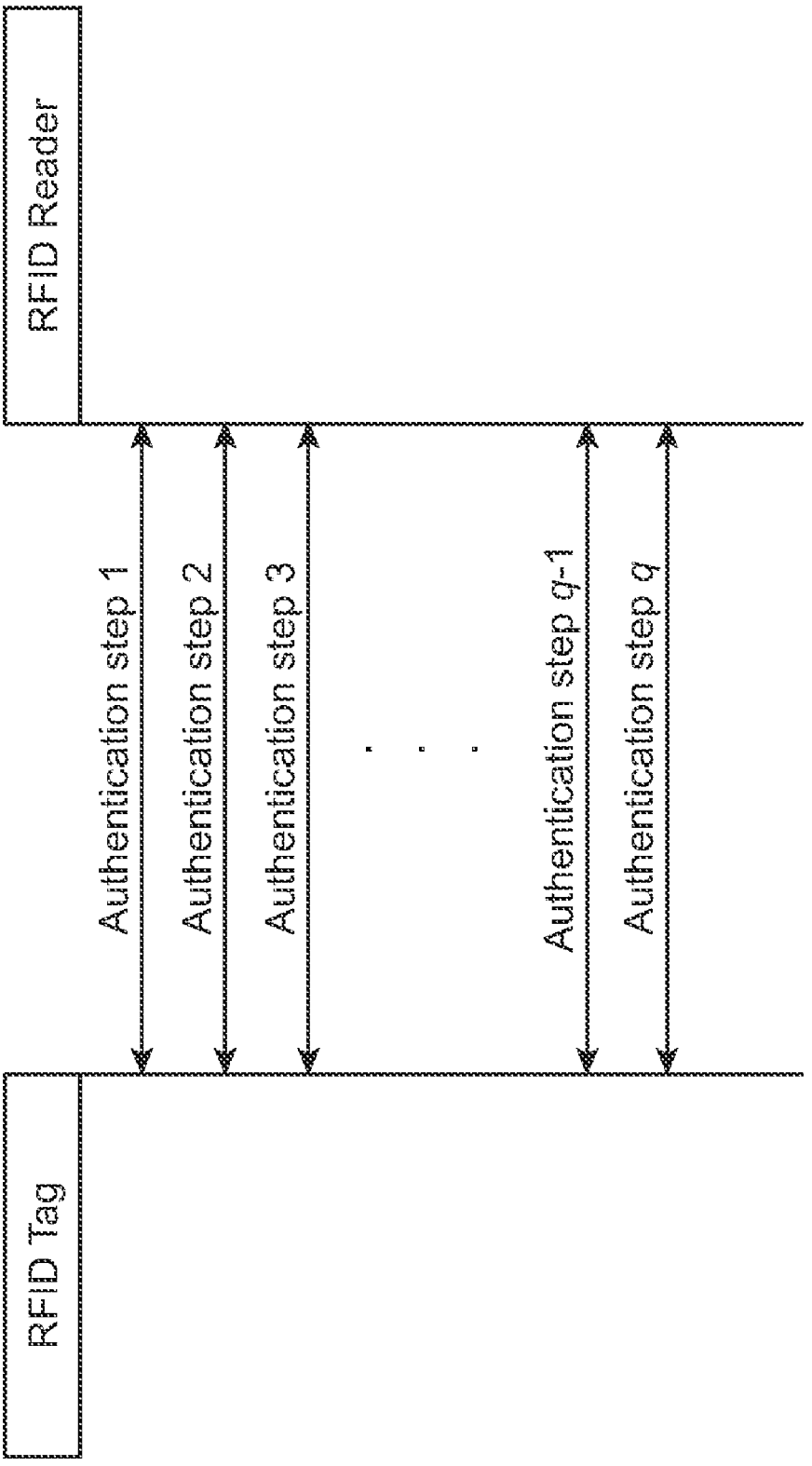

RFID Reader
Authentication step 1
Authentication step 2
Authentication step 3
Authentication step q-1
Authentication step q
RFID Tag

FIG. 1

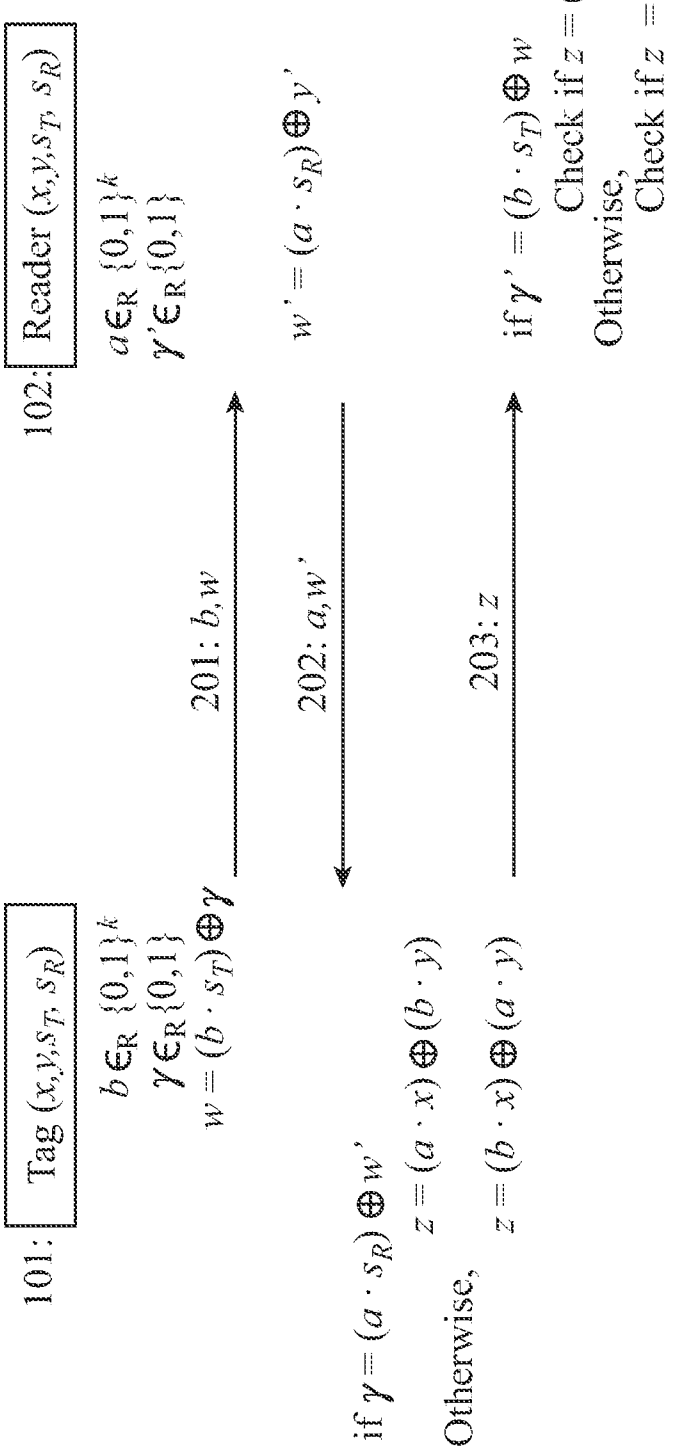

101: Tag (x,y,s_T, s_R)
102: Reader (x,y,s_T, s_R)
$b \in_R \{0,1\}^k$
$\gamma \in_R \{0,1\}$
$w = (b \cdot s_T) \oplus \gamma$
201: b,w
$a \in_R \{0,1\}^k$
$\gamma' \in_R \{0,1\}$
$w' = (a \cdot s_R) \oplus y'$
202: a,w'
if $\gamma = (a \cdot s_R) \oplus w'$
$z = (a \cdot x) \oplus (b \cdot y)$
Otherwise,
$z = (b \cdot x) \oplus (a \cdot y)$
203: z
if $\gamma' = (b \cdot s_T) \oplus w$
Check if $z = (a \cdot x) \oplus (b \cdot y)$
Otherwise,
Check if $z = (a \cdot y) \oplus (b \cdot x)$

FIG. 2

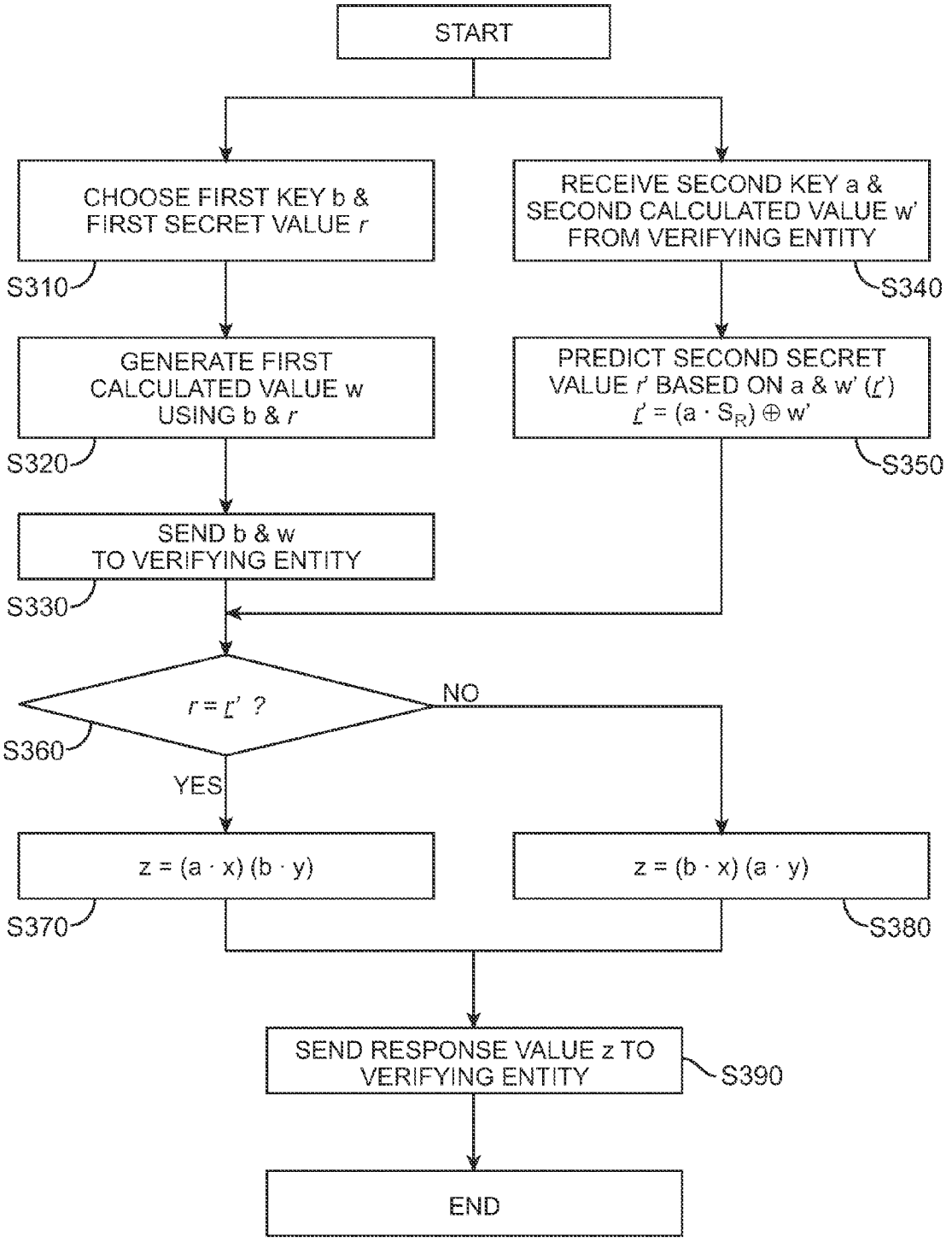

START
CHOOSE FIRST KEY b & FIRST SECRET VALUE r
S310
GENERATE FIRST CALCULATED VALUE w USING b & r
S320
SEND b & w TO VERIFYING ENTITY
S330
RECEIVE SECOND KEY a & SECOND CALCULATED VALUE w' FROM VERIFYING ENTITY
S340
PREDICT SECOND SECRET VALUE r' BASED ON a & w' (r')
r' = (a · S_R) ⊕ w'
S350
r = r' ?
S360
NO
YES
z = (a · x) (b · y)
S370
z = (b · x) (a · y)
S380
SEND RESPONSE VALUE z TO VERIFYING ENTITY
S390
END

FIG. 3

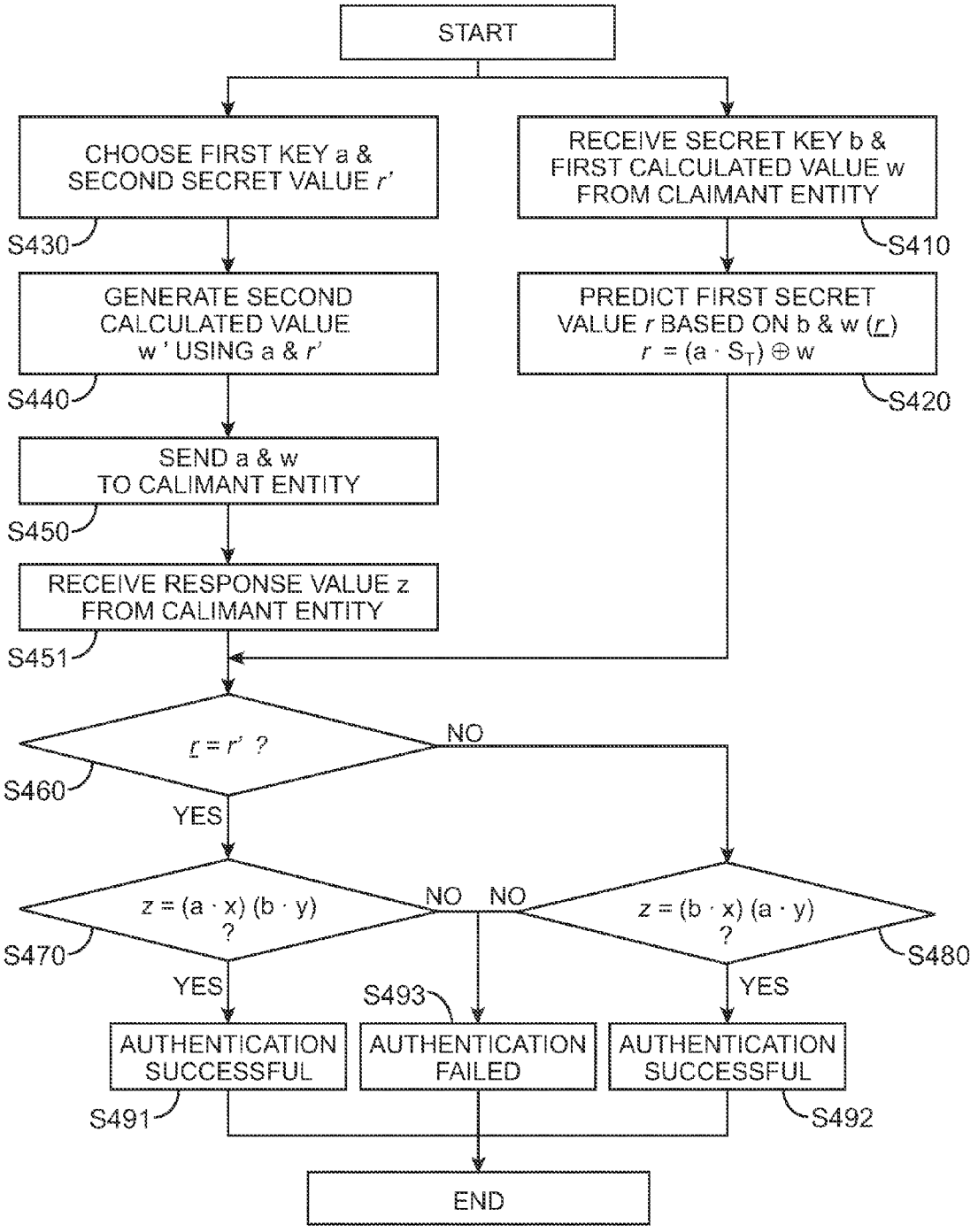

START
CHOOSE FIRST KEY a & SECOND SECRET VALUE r'
S430
GENERATE SECOND CALCULATED VALUE w ' USING a & r'
S440
SEND a & w TO CALIMANT ENTITY
S450
RECEIVE RESPONSE VALUE z FROM CALIMANT ENTITY
S451
RECEIVE SECRET KEY b & FIRST CALCULATED VALUE w FROM CLAIMANT ENTITY
S410
PREDICT FIRST SECRET VALUE r BASED ON b & w (r)
r = (a · S_T) ⊕ w
S420
r = r' ?
S460
NO
YES
z = (a · x) (b · y) ?
S470
NO
NO
z = (b · x) (a · y) ?
S480
YES
YES
S493
AUTHENTICATION SUCCESSFUL
S491
AUTHENTICATION FAILED
AUTHENTICATION SUCCESSFUL
S492
END

FIG. 4

LIGHTWEIGHT AUTHENTICATION METHOD, SYSTEM, AND KEY EXCHANGE PROTOCOL FOR LOW-COST ELECTRONIC DEVICES

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] Aspects of the present invention relate to an authentication method, protocol and system for verifying authenticity of an entity such as a radio frequency identification (RFID) tag, a sensor node, or the like.

[0003] 2. Description of the Related Art

[0004] Entity authentication involves sending an identity or characteristic information by one entity using wired or wireless communication network, and executing a protocol to authenticate the received information by a responding entity. The authentication mainly uses symmetric key or public key.

[0005] Symmetric key-based authentication is a protocol by which entities participating in authentication exchange share a secret key on a one-to-one basis. This symmetric key authentication can guarantee high security, and entities involved in the authentication exchange can have symmetricity. However, the symmetric key authentication suffers from several shortcomings. That is, a large storage space is required to store secret keys, since symmetric key authentication requires that separate secret keys be generated and managed for each of the counterpart entities. Besides, a complicated hardware is required to manage the secret keys.

[0006] Public key-based authentication can be used between a verifying entity (verifier) to authenticate a counterpart and a claimant entity (claimant) attempting to be authenticated, in which the entities involved in the authentication exchange share a public key provided by a public organization. The public key-based authentication may be executed asymmetrically. For example, if a device such as a RFID reader is the verifier and RFID tags are the claimants, the verifier and the claimants A and B can share a public key, while the claimant A and verifier share a secret key A to execute authentication. The claimant B and the verifier can share a secret key B to perform authentication.

[0007] While the verifier stores therein and manages all the keys required for authentication, including the secret keys A and B and the public key for the authentication with the claimants A and B, the claimant A stores the public key and secret key A, and the claimant B stores the public key and secret key B.

[0008] The symmetric key authentication and public key authentication protocols need complicated authentication processes at the claimants to ensure high security. To perform complicated authentication processes, the hardware of the claimants has increased complexity and thus becomes more expensive. This makes the above authentication protocols unsuitable for use on a low-cost device such as RFID tag.

[0009] Accordingly, there is a need for an authentication protocol for use with a RFID tag, which is capable of executing efficient authentication without requiring a complicated hardware.

SUMMARY OF THE INVENTION

[0010] Aspects of the present invention provide an authentication system in which a verifying entity to authenticate its counterpart and a claimant entity attempting to be authenticated, independently generate and send keys to one another and thus are secure against man-in-the-middle attack.

[0011] Aspects of the present invention also provide an authentication system and method which do not require additional primitive. The authentication system and method allow flexibility in choosing security parameter. Accordingly, with the optimized choice, the authentication system can have further increased security. The authentication system and method can be used as a key exchange protocol without requiring additional steps.

[0012] Aspects of the present invention also provide an authentication system and method which do not suffer from incompleteness problem.

[0013] In accordance with an example embodiment of the present invention, there is provided an authentication system including a verifying entity to authenticate a counterpart and a claimant entity attempting to be authenticated, in which the claimant entity sends a first calculated value to the verifying entity, the verifying entity sends a second calculated value to the claimant entity, the claimant entity sends a response value to the verifying entity in response, and the verifying entity authenticates the response value using the first calculated value.

[0014] In accordance with another example embodiment of the present invention, there is provided an authentication method according to which a verifying entity to authenticate a counterpart and a claimant entity attempting to be authenticated, share a plurality of secret keys and the claimant entity performs authentication by communicating with the verifying entity. The authentication method may include: generating a first calculated value using a first key and a first secret value, sending the first key and the first calculated value to the verifying entity, receiving from the verifying entity a second key and a second calculated value, the second calculated value being generated using the second key and a second secret value, predicting the second secret value that corresponds to the second calculated value, using the second key and the second calculated value, generating a response value based on the predicted second calculated value, and sending the response value to the verifying entity.

[0015] In accordance with another example embodiment of the present invention, there is provided an authentication method according to which a verifying entity to authenticate a counterpart and a claimant entity attempting to be authenticated, share a plurality of secret keys and the verifying entity authenticates the claimant entity. The authentication method may include receiving from the claimant entity a first key and a first calculated value, the first calculated value being generated using the first key and a first secret value, generating a second calculated value using a second key and a second secret value, sending the second key and the second calculated value to the claimant entity, receiving a response value from the claimant entity, predicting the first secret value using the first key and the first calculated value, and verifying the response value based on the predicted first secret value.

[0016] Additional aspects and/or advantages of the invention will be set forth in part in the description which follows and, in part, will be obvious from the description, or may be learned by practice of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] These and/or other aspects and advantages of the invention will become apparent and more readily appreciated

from the following description of the embodiments, taken in conjunction with the accompanying drawings of which:

[0018] FIG. **1** illustrates a process of executing q rounds of authenticating steps between a radio frequency identification (RFID) tag and a RFID reader according to an exemplary embodiment of the present invention;

[0019] FIG. **2** illustrates in detail one authentication step execute between a RFID tag and a RFID reader according to an exemplary embodiment of the present invention;

[0020] FIG. **3** is a flowchart illustrating in detail a process of authentication executed at the RFID tag of FIG. **2** according to an exemplary embodiment of the present invention; and

[0021] FIG. **4** is a flowchart illustrating in detail a process of authentication executed at the RFID reader of FIG. **2** according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0022] Reference will now be made in detail to the example embodiments of the present invention, examples of which are illustrated in the accompanying drawings, wherein like reference numerals refer to like elements throughout. The embodiments are described below in order to explain the aspects of the present invention by referring to the figures.

[0023] HB authentication protocol proposed by Hopper and Blum brought new approach to designing lightweight cryptographic protocols. HB authentication protocol is based on a new foundation called Learning Parity with Noise (LPN) problem. The core operation in the LPN problem is binary inner-product which requires just a linear number of XOR and AND operations.

[0024] LPN problem has been extensively studied and known to be nondeterministic polynomial-complete (NP-complete).

[0025] It is known to take $2^{O(n/\log n)}$ even for the fastest algorithm to solve the LPN problem.

[0026] Unfortunately, HB protocol is designed for human-to-computer authentication, and cannot be used for device-to-device authentication. An improved protocol called HB+proposed by Juels and Weis made it possible to use this kind of protocol for device-to-device authentication.

[0027] However, HB+ protocol is not satisfactorily secure against a stronger attack called 'man-in-the-middle attack'. The 'man-in-the-middle attack' is a type of attack that intercepts secret information sent and received between a verifying entity ('verifier') such as a RFID reader and a claimant entity ('claimant') such as a RFID tag, and relays tampered information.

[0028] Furthermore, both HB and HB+ suffer from a problem called incompleteness. That is, even though genuine claimant and verifier follow protocols correctly, there is still a chance that authentication may fail.

[0029] The authentication system and method according to an exemplary embodiment of the present invention use a cryptography based on HB protocol, is secure against man-in-the-middle attack, and does not suffer from incompleteness problem.

[0030] FIG. **1** illustrates q rounds of authentication steps executed between a RFID reader as a verifier and a RFID tag as a claimant.

[0031] Efforts have constantly been made to make it easier to identify persons or products especially in the field of commerce. The identity cards or passwords can be the typical examples of the ways to verify the identity of a person, and these traditional methods have appropriately been adapted for use on electronic devices.

[0032] However, passwords are easily exposed or stolen. For example, a malicious attacker may steal a credit card password and withdraw deposit from a credit card owner's account.

[0033] The magnetic card or radio frequency identification (RFID) is the technology introduced to prevent one's identity or password from being exposed to such a potential identity thief. The RFID enables recognition of information in from several centimeters to several meters of distance depending on the design.

[0034] The speed of recognition is approximately 0.01~0.1 seconds, which is faster and less subjective to an external influence than the other types of media such as magnetic.

[0035] The RFID technology chip also can store relatively a large amount of information.

[0036] The RFID technology is achieved by data transmission and reception between a RFID reader and a RFID tag. The RFID tag may include an integrated circuit (IC) to store information, and an antenna. The capacity of the RFID tag to store information depends on the size of memory embedded in the IC chip.

[0037] The RFID reader may provide energy to operate the RFID tag. The RFID reader may send a command, requesting the RFID tag to perform a specific operation. Accordingly, in response to the command from the RFID reader, the RFID tag may send data to the RFID reader.

[0038] The RFID reader and RFID tag may communicate in an inductively coupled manner, or by using electromagnetic waves. The inductively coupled scheme is generally used for short distance communication which is generally within 1 meter, while the electromagnetic wave-based scheme is generally used for middle, or long distance communication exceeding **1** meter.

[0039] The energy to operate the RFID tag may be provided by the RFID reader. Alternatively, the RFID tag may be connected to an energy source such as a battery.

[0040] According to an exemplary embodiment of the present invention, a verifier, including RFID reader, may request a claimant, including RFID tag, a response. If the claimant sends a response message to the verifier in response, the verifier determines whether or not the response message meets a predetermined rule. If the received response message meets the predetermined rule, the verifier determines the claimant to be a genuine entity and thus gives an access to the information stored in the verifier.

[0041] However, if the response message from the claimant does not meet the predetermined rule, the verifier determines authentication to have failed, and refuses the access of the claimant to the verifier.

[0042] According to an exemplary embodiment of the present invention, if the authentication is successful, the verifier may additionally read data stored in the claimant, and update the data previously stored in the verifier based on the read data. In this case, the verifier may send a data request command to the claimant, and the claimant may send the requested data to the verifier in response.

[0043] According to an exemplary embodiment of the present invention, the verifier may include, or be connected to a database to store information about the registered claimants.

[0044] According to an exemplary embodiment of the present invention, the verifier may control a mobile device.

Accordingly, if authentication is successful, the verifier may allow the claimant to use the mobile device.

[0045] The operation of the verifier requesting a response from the claimant, and determining authentication to be a success or failure based on the received response message, may form one authentication step.

[0046] The authentication steps may be executed independently, and authentication is considered to be successful if all q rounds of authentication steps are successful. The q steps may be executed in parallel or sequentially.

[0047] The verifier and the claimant may generate session bits in each of the authentication steps, and thus generate q-bit session keys throughout the q steps.

[0048] FIG. **2** illustrates in detail each of the authentication step of FIG. **1** according to an exemplary embodiment of the present invention.

[0049] A tag **101** and a reader **102** share four shared secret keys (x, y, S_T, S_R). The tag **101** may store the four shared secret keys in its internal memory.

[0050] The tag **101** generates a k-bit first key b randomly.

[0051] Each of the first key b may have one of the values {0, 1}.

[0052] The tag **101** may choose a 1-bit first secret value r randomly.

[0053] The tag **101** may compute a binary inner-product, that is, $(b \cdot S_T)$ of the first key b and the first shared secret key S_T. The tag **101** generates a first calculated value w by computing logical XOR operation of $(b \cdot S_T)$ and the first secret value r.

[0054] The first calculated value w may be expressed by:

$$w=(b \cdot S_T) \oplus r \qquad \text{[Mathematical formula 1]}$$

where $\oplus$ denotes logical XOR operation.

[0055] The binary inner-product of the k-bit bit streams may be computed as explained below.

[0056] For example, given $a=(a_0 a_1 a_2 \ldots a_{(k-1)})_2$ and, $x=(x_0 x_1 x_2 \ldots x_{(k-1)})_2$, the binary inner-product (a·x) of a and x may be computed by:

$$a \cdot x=(a_0 \wedge x_0) \oplus (a_1 \wedge x_1) \oplus \ldots \oplus (a_{(k-1)} \wedge x_{(k-1)}) \qquad \text{[Mathematical formula 2]}$$

where $\wedge$ denotes logical AND operation.

[0057] The tag **101** sends the first key b and the first calculated value w to the reader **102**.

[0058] The reader **102** generates a k-bit second key a randomly.

[0059] Each bit of the second key a may have one of the values {0, 1}.

[0060] The reader **102** may choose a 1-bit second secret value r' randomly.

[0061] The reader **102** may compute a binary inner-product $(a \cdot S_R)$ of the second key a and the second shared secret key S_R. The reader **102** may generate a second calculated value w' by computing logical XOR operation of the binary inner-product $(a \cdot S_R)$ and the second secret value r'.

[0062] The second calculated value w' may be expressed by:

$$w'=(a \cdot S_R) \oplus r' \qquad \text{[Mathematical formula 3]}$$

[0063] The reader **102** sends the second key a and the second calculated value w' to the tag **101**.

[0064] The tag **101** may obtain a predicted second secret value $\underline{r}'$, using the second key a and the second calculated value w' as received. The predicted second secret value $\underline{r}'$ may be expressed by:

$$\underline{r}'=(a \cdot S_R) \oplus w' \qquad \text{[Mathematical formula 4]}$$

[0065] The tag **101** determines if the predicted second secret value $\underline{r}'$ matches the first secret value r, and determines to choose one of a first and second encryption equations according to whether or not the predicted second secret value $\underline{r}'$ matches the first secret value r.

[0066] That is, if the predicted second secret value $\underline{r}'$ matches the first secret value r, the tag **101** generates a response value z using the first encryption equation.

[0067] The response value z may be expressed by:

$$z=(a \cdot x) \beta (b \cdot y) \qquad \text{[Mathematical formula 5]}$$

where x, y are shared secret keys shared by the tag **101** and the reader **102**.

[0068] If the predicted second secret value $\underline{r}'$ does not match the first secret value r, the tag **101** generates a response value z using the second encryption equation.

[0069] The response value z may be expressed by:

$$z=(b \cdot x) \oplus (a \cdot y) \qquad \text{[Mathematical formula 6]}$$

where x, y are shared secret keys shared by the tag **101** and the reader **102**.

[0070] The tag **101** sends a response value z to the reader **102**.

[0071] The reader **102** predicts a first secret value r using the received first key a and first calculated value w.

[0072] The predicted first secret value r may be expressed by:

$$\underline{r}=(b \cdot S_T) \oplus w \qquad \text{[Mathematical formula 7]}$$

[0073] The reader **102** determines whether the predicted first secret value v matches the second secret value r'. Depending on whether the predicted first secret value $\underline{r}$ matches the second secret value r' or not, the reader **102** chooses one of the first and second encryption equations.

[0074] If the first secret value r matches the second secret value r', the reader **102** checks a response value z using the first encryption equation. However, if the predicted first secret value $\underline{r}$ does not match the second secret value r', the reader **102** checks the response value z using the second encryption equation.

[0075] In other words, the reader **102** considers authentication to be successful if the predicted first secret value $\underline{r}$ matches the second secret value r' and $z=(a \cdot x) \oplus (b \cdot y)$. The reader **102** may also considers authentication to be successful if the predicted first secret value r does not match the second secret value r' and $z=(b \cdot x) \oplus (a \cdot y)$.

[0076] The tag **101** and the reader **102** may share securely the result of $r \oplus r'$, which is the XOR operation of the first and second secret values r, r'.

[0077] The tag **101** and the reader **102** may share $r \oplus r'$ whenever each authentication step succeeds, and if q authentication steps are successful, may use the q-bit shared values as session keys.

[0078] The tag **101** and the reader **102** may update the previously shared secret keys (x, y, S_T, S_R) using the session keys.

[0079] The tag **101** and the reader **102** may generate keys and secret values independently, and generate calculated values using the shared secret keys. The tag **101** and the reader **102** may send the key and the calculated value to the counterparts.

[0080] The authentication protocol according to the exemplary embodiments of the present invention can be called a HB* (read HB star) protocol.

[0081] The calculated value can be interpreted only by the combination with the previously shared secret key. Accordingly, even if the calculated value is exposed during data transaction between the tag **101** and the reader **102**, the chance of having the secret value exposed is reduced.

[0082] The tag **101** and the reader **102** generate keys and calculated values independently and send the generated keys and values to one another. The tag **101** and the reader **102** generate or authenticate a response value using the key and calculated value, which are independently generated and received from one another, and thus can remain secure even if calculated value is intercepted by the man-in-the-middle attack. That is, the tag **101** alone involves in the generation of the first key b and the first calculated value w, while the reader **101** is not involved. Likewise, only the reader **102** involves in the generation of the second key a and the second calculated value w'.

[0083] Since the tag **101** and the reader **102** use the keys and the calculated values generated only by themselves, successful authentication is impossible by intercepting the calculated value, i.e., by the man-in-the-middle attack.

[0084] The tag **101** and the reader **102** may perform encryption based on Learning Parity with Noise (LPN) problem. Since hardware can be realized with the simple AND and XOR operations, the complexity of hardware at the tag **101** and the reader **102** can be reduced significantly.

[0085] Choosing the first or second secret value r or r' may be drawn by the arbitrary probability distribution. The second secret value r or r' can be chosen from the uniform probability distribution which leads to the hardest instance of LPN problem.

[0086] The tag **101** may compute a response value using one of two formulas according to the values of r and r'. Therefore, No noise needs to be applied to the response value. The response value may be generated using a shared secret key, or a key sent to or received from the reader **102**.

[0087] As a result, the reader **102** can ensure successful authentication of a genuine tag **101**. The tag **101** and the reader **102** may provide a perfectly complete protocol.

[0088] FIG. **3** is a flowchart illustrating in detail the authentication executed at the tag **101** of FIG. **2** according to an exemplary embodiment of the present invention.

[0089] The tag **101** chooses a first key b and a first secret value r at S**310**. In this situation, the tag **101** may choose the first key b and the first secret value r based on the random probability distribution.

[0090] The tag **101** generates a first calculated value w using the first key b and the first secret value r at S**320**. The first calculated value w may be generated using mathematical formula 1 explained above. The tag **101** computes binary inner-product of the first key b and the first shared secret key S_T, and performs logical XOR operation of the binary inner-product and the first secret value r to generate a first calculated value w.

[0091] The tag **101** sends the first key b and the first calculated value w to the reader **102** at S**330**. Since the data (or codeword) sent from the tag **101** to the reader **102**, does not directly include the first secret value r, the first secret value r is not directly exposed even when the codeword is intercepted during transmission.

[0092] The tag **101** receives a second key a and a second calculated value w' from the reader **102** at S**340**.

[0093] The tag **101** predicts a second secret value r' based on the second key a and the second calculated value w' at S**350**. The predicted second secret value $\underline{r}'$ may be computed using mathematical formula 4 explained above. The tag **101** computes binary inner-product of the second key a and the second shared secret key S_R, and computes the predicted second secret value $\underline{r}'$ based on the result of logical XOR operation of the binary inner-product and the second calculated value w'.

[0094] The operations at S**310** to S**330** may be performed in parallel with the operations at S**340** to S**350**, or alternatively, these operations may be performed sequentially. The operations at S**310** to **330** may also be performed independently from the operations at S**340** to S**350**.

[0095] The tag **101** determines whether or not the first secret value r and the predicted second secret value $\underline{r}'$ match at S**360**. Although FIG. **3** exemplarily depicts that S**320** to S**330** are performed prior to S**360**, according to an alternative example, S**320** to S**330** may be performed in parallel with S**360** to S**390**, or sequentially.

[0096] If the first secret value r and the predicted second secret value $\underline{r}'$ match, the tag **101** generates a response value z using the first encryption equation at S**370**. The response value z may be computed using mathematical formula 5 explained above.

[0097] If the first secret value r and the predicted second secret value $\underline{r}'$ do not match, the tag **101** generates a response value z using the second encryption equation at S**380**. The response value z may be computed using mathematical formula 6 explained above.

[0098] The tag **101** sends the response value z, either generated at S**370** or S**380**, to the reader **102** at S**390**.

[0099] The tag **101** may perform an additional step of generating a session key by computing logical XOR operation of the first secret value r and the predicted second secret value $\underline{r}'$. Since the tag **101** generates a response value z using the first secret value r and the first key a generated at the tag **101**, and the predicted second secret value$\underline{r}'$ generated at the reader **102** and predicted at the tag **101** and the second key b, it is necessary that the man-in-the-middle attack intercepts all the codeword transmitted from the tag **101** to the reader **102** and vice versa in order to access the authentication system of the tag **101** and the reader **102**. Therefore, the authentication system between the tag **101** and the reader **102** can increase security against the man-in-the-middle attack.

[0100] FIG. **4** is a flowchart illustrating in detail authentication executed at the reader **102** of FIG. **2** according to an exemplary embodiment of the present invention.

[0101] The reader **102** receives a first key b and a first calculated value w from the tag **101** at S**410**.

[0102] The reader **102** predicts the first secret value r using the first key b and the first calculated value w at S**420**. The predicted first secret value $\underline{r}$ may be computed by mathematical formula 7 explained above. The reader **102** computes binary inner-product of the first key b and the first shared secret key S_T, and computes the predicted first secret value $\underline{r}$ by performing logical XOR operation of the binary inner-product and the first calculated value w.

[0103] The reader **102** choose a second key a and a second secret value r' at S**430**. The reader **102** may choose the second key a and the second secret value r' based on the random probability distribution.

[0104] The reader **102** generates a second calculated value w' using the second key a and the second secret value r' at S**440**. The second calculated value w' may be computed based on mathematical formula 3 explained above. The reader **102**

computes binary inner-product of the second key a and the second shared secret key S_R, and generates a second calculated value w' by performing logical XOR operation of the binary inner-product and the second secret value r'.

[0105] The reader **102** sends the second key a and the second calculated value w' to the tag **101** at S**450**. The reader **102** receives a response value z from the tag **101** at S**451**. The response value z corresponds to the second key a and the second calculated value w'.

[0106] The operations at S**410** to S**420** may be performed independently from the operations at S**430** to S**451**. The operations at S**410** to S**420** may be performed in parallel with the operations at S**430** to S**450**, or sequentially.

[0107] The reader **102** may determine whether the predicted first secret value r and the second secret value r' match at S**460**.

[0108] If the predicted first secret value r matches the second secret value r', the reader **102** determines whether or not the response value z meets the first encryption equation S**470**. The first encryption equation may be expressed by mathematical formula 5.

[0109] If the response value z meets the first encryption equation, the reader **102** determines authentication to be successful at S**491**. If the response value z does not meet the first encryption equation, the reader **102** determines authentication to have failed at S**493**.

[0110] If the predicted first secret value r does not match the second secret value r', the reader **102** determines whether or not the response value z meets the second encryption equation at S**480**. The second encryption equation may be expressed by mathematical formula 6.

[0111] If the response value z meets the second encryption equation, the reader **102** determines authentication to be successful at S**492**. If the response value z does not meet the second encryption equation, the reader **102** considers authentication to have failed at S**493**.

[0112] The reader **102** verifies the response value z, using not only the second key a and the second secret value r' generated at the reader **102** and the predicted first secret value r predicted by the reader **102** and the first key b, but also the first shared secret key S_T and the second shared secret key S_R shared by the tag **101** and the reader **102**. Since the codeword (b, w) of the reader **102**, and the codeword (a, w') of the tag **101** are generated by an independent process, the authentication system of the reader **102** and the tag **101** is secure against the man-in-the-middle attack.

[0113] The method according to the exemplary embodiments of the present invention may be realized as a program command which can be executed by a variety of computer means, and recorded on a computer-readable medium. The 'computer-readable medium' herein may refer to a program command, data file, data structure, or any combination thereof. The program command recorded on the medium may be designed and constructed specifically for application of the exemplary embodiments of the present invention, or alternatively, the program command may be that which is already known to and used by those skilled in the field of computer software. The computer readable medium may include a magnetic media such as hard disk, floppy disk or magnetic tape, an optical media such as CD-ROM or DVD, a magneto-optical media such as floptical disk, and a hardware device such as ROM, RAM or flash memory, which is constructed specifically to store and execute the program command. The program command may include not only a mechanical language code which is constructed by a compiler, but also an advanced language code which can be executed on a computer using appropriate tool such as an interpreter. The hardware device may be designed to operate as one or more software modules to execute the steps according to the exemplary embodiments of the present invention, or the opposite is also possible.

[0114] While there have been illustrated and described what are considered to be example embodiments of the present invention, it will be understood by those skilled in the art and as technology develops that various changes and modifications, may be made, and equivalents may be substituted for elements thereof without departing from the true scope of the present invention. Many modifications, permutations, additions and sub-combinations may be made to adapt the teachings of the present invention to a particular situation without departing from the scope thereof.

[0115] Accordingly, it is intended, therefore, that the present invention not be limited to the various example embodiments disclosed, but that the present invention includes all embodiments falling within the scope of the appended claims.

What is claimed is:

1. An authentication method according to which a claimant entity attempting to be authenticated and a verifying entity to authenticate the claimant entity, share a plurality of secret keys and authentication is processed as the claimant responds to a challenge by the verifying entity, the authentication method comprising:

generating a first calculated value using a first key and a first secret value;

sending the first key and the first calculated value to the verifying entity;

receiving from the verifying entity a second key and a second calculated value, the second calculated value being generated using the second key and a second secret value;

predicting the second secret value that corresponds to the second calculated value, using the second key and the second calculated value;

generating a response value based on the predicted second calculated value; and

sending the response value to the verifying entity.

2. The authentication method of claim **1**, wherein the generating of the first calculated value comprises:

choosing the first secret value randomly;

computing a binary inner-product of a first shared secret key shared with the verifying entity and the first key; and

generating the first calculated value by performing logical exclusive OR operation of the binary inner-product and the first secret value.

3. The authentication method of claim **1**, wherein the predicting of the second secret value comprises:

computing binary inner-product of a second shared secret key shard with the verifying entity and the second key; and

performing logical exclusive OR operation of the binary inner-product and the second calculated value.

4. The authentication method of claim **1**, wherein the generating of the response value comprises:

determining whether of not the predicted second secret value matches the first secret value;

generating the response value, using the first key, the second key and a first encryption equation, if the predicted second secret value matches the first secret value; and

generating the response value, using the first key, the second key and a second encryption equation, if the predicted second secret value does not match the first secret value.

5. The authentication method of claim **1**, wherein the steps of the generating of the first calculated value, the sending of the first key and the first calculated value, the receiving of the second key and the second calculated value, the predicting of the second secret value, the generating of the response value, and the sending of the response value, are repeated a plurality of times, and authentication of the verifying entity is determined to be successful if authentication of all the repeated steps succeeds.

6. The authentication method of claim **1**, further comprising generating a session secret value by performing logical exclusive OR operation of the first secret value and the predicted second secret value.

7. An authentication method according to which a claimant entity attempting to be authenticated and a verifying entity to authenticate the claimant entity, share a plurality of secret keys and authentication is processed as the claimant responds to a challenge by the verifying entity, the authentication method comprising:

receiving from the claimant entity a first key and a first calculated value, the first calculated value being generated using the first key and a first secret value;

generating a second calculated value using a second key and a second secret value;

sending the second key and the second calculated value to the claimant entity;

receiving a response value from the claimant entity;

predicting the first secret value using the first key and the first calculated value; and

verifying the response value based on the predicted first secret value.

8. The authentication method of claim **7**, wherein the predicting of the first secret value comprises:

computing binary inner-product of a first shared secret key shared with the claimant entity and the first key; and

performing logical exclusive OR operation of the binary inner-product and the first calculated value.

9. The authentication method of claim **7**, wherein the generating of the second calculated value comprises:

choosing the second calculated value randomly;

computing binary inner-product of a second shared secret key shared with the claimant entity and the second key; and

generating the second calculated value by performing logical exclusive OR operation of the binary inner-product and the second secret value.

10. The authentication method of claim **7**, wherein the verifying of the response value comprises:

determining whether or not the predicted first secret value matches the second secret value;

generating a first authentication value using the first key, the second key and a first encryption equation, if the predicted first secret value matches the second secret value;

determining authentication to be successful if the first authentication value matches the response value;

generating a second authentication value using the first key, the second key and a second encryption equation, if the predicted first secret value does not match the second secret value; and

determining authentication to be successful if the second authentication value matches the response value.

11. The authentication method of claim **7**, wherein the steps of the receiving of the first key and the first calculated value, the generating of the second calculated value, the sending of the second key and the second calculated value, the receiving of the response value, the predicting of the first secret value, and the verifying of the response value, are repeated a plurality of times, and authentication of the verifying entity is determined to be successful if authentication of all the repeated steps succeeds.

12. The authentication method of claim **7**, further comprising generating a session secret value by performing logical exclusive OR operation of the predicted first secret value and the second secret value.

13. An authenticating system, comprising a verifying entity and a claimant entity,

wherein the claimant entity sends a first calculated value to the verifying entity, the verifying entity sends a second calculated value to the claimant entity, the claimant entity sends a response value to the verifying entity in response, and the verifying entity authenticates the response value using the first calculated value.

14. The authentication system of claim **13**, wherein the claimant entity and the verifying entity share a first and second shared secret keys,

the claimant entity generates the first calculated value using a first key, a first secret value, and the first shared secret key, and sends the first key along with the first calculated value to the verifying entity, and

the verifying entity generates the second calculated value using a second key, a second secret value, and the second shared secret key, and sends the second key along with the second calculated value to the claimant entity.

15. The authentication system of claim **13**, wherein the claimant entity

predicts the second secret value using the second calculated value, the second key and the second shared secret key,

chooses one of a first encryption equation and a second encryption equation, depending on whether or not the predicted second secret value matches the first secret value, and

generates the response value using the encryption equation chosen from among the first and second encryption equations, and the first and second keys.

16. The authentication system of claim **13**, wherein the verifying entity

predicts the first secret value using the first calculated value, the first key and the first shared secret key,

chooses one of a first encryption equation and a second encryption equation depending on whether or not the predicted first secret value matches the second secret value,

generates an authentication value using the chosen one from among the first and second encryption equations and the first and second keys, and

determines authentication to be successful if the authentication value matches the response value.

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