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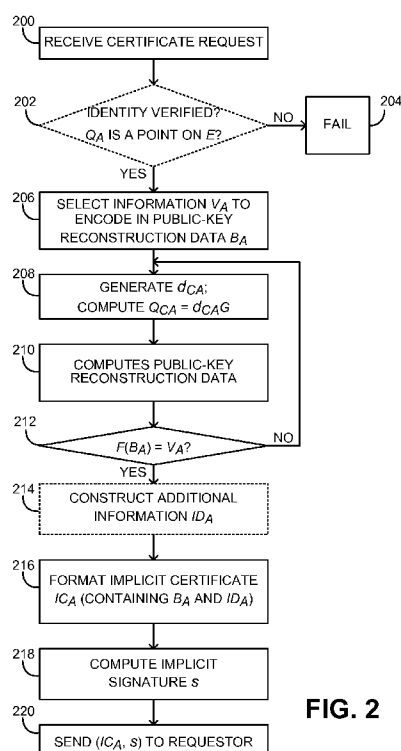
(54) **Title:** INCORPORATING DATA INTO CRYPTOGRAPHIC COMPONENTS OF AN ECQV CERTIFICATE

FIG. 2

(57) **Abstract:** During generation of an implicit certificate (102, 638) for a requestor (100, 600), a certificate authority (104, 620) incorporates information in the public-key reconstruction data (110), where the public-key reconstruction data is to be used to compute the public key (648) of the requestor. The information may be related to one or more of the requestor, the certificate authority, and the implicit certificate. The certificate authority reversibly encodes the public-key reconstruction data in the implicit certificate and sends it to the requestor. After receiving the implicit certificate from the certificate authority, the requestor can extract the incorporated information from the public-key reconstruction data. The implicit certificate can be made available to a recipient (114, 654), and the recipient can also extract the incorporated information.



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INCORPORATING DATA INTO CRYPTOGRAPHIC COMPONENTS OF AN ECQV CERTIFICATE

TECHNICAL FIELD

[0001] The technology described herein relates generally to elliptic curve cryptography, and particularly to the generation of cryptographic keys, implicit certificates and digital signatures.

BACKGROUND

[0002] Elliptic curve cryptography (ECC) is based on the intractability of the discrete logarithm problem within a group over a finite field where the elements of the group are points on an elliptic curve. Cryptographic values generated using ECC schemes, such as the Elliptic Curve Digital Signature Algorithm (ECDSA), may be smaller than those generated using finite-field cryptography schemes, such as the Digital Signature Algorithm (DSA) and integer factorization cryptography schemes, such as the Rivest Shamir Adleman (RSA) algorithm, while still offering the same level of security. Smaller-sized cryptographic values are desirable because they may reduce storage and transmission requirements. ECDSA is described, for example, in “American National Standard for Financial Services ANS X9.62-2005: Public Key Cryptography for the Financial Services Industry - The Elliptic Curve Digital Signature Algorithm (ECDSA)”, Accredited Standards Committee X9, Inc., 2005. DSA and RSA are described, for example, in “Federal Information Processing Standards Publication 186-3 Digital Signature Standard (DSS)”, National Institute of Standards and Technology, June 2009.

[0003] A digital certificate may be used to bind a public key to its legitimate owner so that a recipient of the certificate can be confident as to the authenticity of the public key. Upon receiving a request from a requestor, a trusted third party, such as a certificate authority (CA), may provide a signed certificate to the requestor who may then send the certificate to a recipient. Alternatively, the recipient may be able to obtain the signed certificate directly from the CA. In a conventional or ‘explicit’ certificate scheme, the signature portion of the certificate is explicitly verified by the recipient in order to confirm that the public key contained in the certificate belongs to the purported owner (i.e., the requestor of the

certificate). Subsequent communication between the requestor and the recipient is authenticated separately using, for example, a key agreement scheme or a digital signature scheme.

[0004] In an implicit certificate scheme, such as the Elliptic Curve Qu-Vanstone (ECQV) scheme, the implicit certificate does not explicitly contain the public key of the requestor, but instead contains data that may be used to reconstruct the public key, also known as public-key reconstruction data. Because the public key is not explicitly contained in the implicit certificate, the authenticity of the reconstructed public key can only be established after it is subsequently used in a successful run of some protocol, such as a key agreement scheme or a digital signature scheme.

[0005] Implicit certificates are generally smaller than explicit certificates and have fewer operational costs because some calculations that are typically performed independently in an explicit certificate scheme can be combined in an implicit certificate scheme. In addition to containing public-key reconstruction data, an implicit certificate also contains separate additional information. This additional information contributes to the size of the implicit certificate.

SUMMARY

[0006] ECC offers an advantage over other cryptographic algorithms, such as DSA and RSA, in that it uses smaller cryptographic values to provide roughly the same level of security. For example, an ECDSA public key that is 160 bits can provide roughly the same level of security as a DSA public key that is 1024 bits. The use of smaller-sized cryptographic values means that related computations require less processing power or less time or both. This makes ECC-based protocols of interest for application environments where resources such as bandwidth, computing power, and storage, are limited.

[0007] ECC-based protocols rely on the intractability of the elliptic curve discrete logarithm problem. Given publicly-known points G and Q on an elliptic curve E , where point Q is equal to a product of a scalar multiplying factor d and point G , that is $Q = dG$, it is conjecturally very difficult to determine scalar multiplying factor d . With known algorithms, the computational difficulty of solving this problem increases exponentially with the size of the subgroup generated by G .

[0008] To implement an ECC-based protocol, all participants must agree on the domain parameters of the elliptic curve. An elliptic curve E defined over a prime finite field $\mathbb{F}_p$, that is $E(\mathbb{F}_p)$, is defined by elliptic curve domain parameters $D = (p, a, b, G, n, h)$, where p is an odd prime number that represents the number of elements in the field, integers a and b are elements of prime finite field $\mathbb{F}_p$ that satisfy, for example, $4a^3 + 27b^2 \not\equiv 0 \pmod{p}$, (however curves specified by another equation may be suitable), G is a base point on elliptic curve $E(\mathbb{F}_p)$ that has order n , where n is defined as the smallest positive prime number such that a product of prime number n and base point G is equal to a point at infinity O , that is $nG = O$, and cofactor h is defined as a ratio of the number of points $\#E(\mathbb{F}_p)$ on elliptic curve $E(\mathbb{F}_p)$ over prime number n , that is $h = \#E(\mathbb{F}_p)/n$. (Alternatively, elliptic curve E could be defined over a characteristic 2 finite field $\mathbb{F}_2^m$, where m is a prime number that is greater than or equal

to one, that is $m \geq 1$.) Arithmetic in subgroups of $E(\mathbb{F}_p)$ may be written additively, where the sum of two points P and Q is $P + Q$, and scalar multiplication by an integer k is kP . Further details of existing ECC-based protocols are described in “Standards for Efficient Cryptography SEC1: Elliptic Curve Cryptography”, Certicom Research, Certicom Corp., 2000, and “Standards for Efficient Cryptography SEC2: Recommended Elliptic Curve Domain Parameters version 2.0”, Certicom Research, Certicom Corp., 2000.

[0009] In addition to satisfying $4a^3 + 27b^2 \not\equiv 0 \pmod{p}$, elliptic curve domain parameters D may need to satisfy other constraints for cryptographic applications. For example, elliptic curve domain parameters D should be generated such that the number of points $\#E(\mathbb{F}_p)$ on elliptic curve $E(\mathbb{F}_p)$ is not equal to the number of elements in prime finite field $\mathbb{F}_p$, that is $\#E(\mathbb{F}_p) \neq p$, and such that odd prime p raised to any integer B , where $1 \leq B \leq 20$, is not equal to one modulo prime number n , that is $p^B \not\equiv 1 \pmod{n}$. Elliptic curve domain parameters D should also be generated such that cofactor h is small, specifically such that cofactor h is less than or equal to four, that is $h \leq 4$, and preferably such that cofactor h is equal to one, that is $h = 1$. Recommended elliptic curve domain parameters D are published by standard bodies, such as the National Institute of Standards and Technology (NIST).

[0010] Once participants have agreed on the domain parameters of an elliptic curve, they can implement ECC-based protocols. Examples of ECC-based protocols include the Elliptic Curve Diffie-Hellman (ECDH) key agreement scheme, the Elliptic Curve Menezes-Qu-Vanstone (ECMQV) key agreement scheme, the Elliptic Curve Integrated Encryption Scheme (ECIES) public-key encryption scheme, and the previously mentioned ECDSA signature scheme.

[0011] Perhaps the simplest example of an ECC-based protocol is the generation of an elliptic curve key pair. Given valid elliptic curve domain parameters $D = (p, a, b, G, n, h)$ associated with an elliptic curve E , an elliptic curve key pair (d, Q) can be generated using the following procedure. First, an integer d is randomly or pseudo-randomly selected within an interval $[1, n - 1]$. Next, integer d is used in a scalar multiplication of base point G to obtain a

new point Q on elliptic curve E , such that $Q = dG$. Scalar multiplication of a point on an elliptic curve, also known as point multiplication, can be computed efficiently using the addition rule with the double-and-add algorithm or one of its variants. These rules are known to those of ordinary skill in the art. Upon determining point Q , the pair (d, Q) can be used as a key pair, where integer d is a private key and point Q is a public key. While the point multiplication used to calculate public key Q from private key d and base point G is relatively straightforward, the inverse of this operation is extremely difficult. In general, ECC-based protocols rely on the difficulty of this operation.

[0012] Generation of a key pair, such as private key d and public key Q as described above, can be done either by a single device with which the key pair is associated, by a trusted third party such as a CA, or interactively between the CA and the device. A key pair can be interactively generated, for example, during the generation of an implicit certificate.

[0013] Similarly to a conventional or ‘explicit’ certificate, an implicit certificate binds public key information to its legitimate owner to provide identity authentication. However, in contrast to an explicit certificate, an implicit certificate does not explicitly contain a public key of the requestor of the implicit certificate. Instead, it contains data that may be used in conjunction with a public key of the CA to reconstruct a public key of the requestor. It should be noted that, while the examples presented herein may refer to “the CA’s private key” or “the requestor’s public key”, for example, it is contemplated that each entity involved in a cryptographic scheme may have more than one public-private key pair. For clarity, only the key pairs that are relevant to the current framework are discussed.

[0014] Implicit certificates are generally smaller than explicit certificates and have fewer operational costs because some calculations that are typically performed independently in an explicit certificate scheme can be combined in an implicit certificate scheme. This makes implicit certificates particularly suited to application environments where resources such as bandwidth, computing power, and storage, are limited. One example of an implicit certificate scheme is the ECQV scheme.

[0015] In addition to the public-key reconstruction data contained in an implicit certificate, the implicit certificate also comprises additional information. This additional information may be related to, for example, one or more of the implicit certificate, the requestor of the implicit certificate, or the public key that is to be computed from the public-

key reconstruction data. This additional information contributes to the size of the implicit certificate.

[0016] A framework is herein proposed whereby, during the generation of an implicit certificate by a certificate authority, information is incorporated in the public-key reconstruction data of the implicit certificate. This information may be related to, for example, one or more of the implicit certificate, a requestor of the implicit certificate, or the public key that is to be computed from the public-key reconstruction data. This information may comprise a validity period of the implicit certificate or a validity date of the implicit certificate or both.

[0017] If a portion of the information to be incorporated in the public-key reconstruction data is a portion that would normally contribute to the additional information of the implicit certificate, the overall size of the implicit certificate can be reduced because the size of the additional information can be reduced by the portion that is incorporated in the public-key reconstruction data. If all of the information that would normally contribute to the additional information of the implicit certificate is incorporated in the public-key reconstruction data, the size of the implicit certificate can be reduced to the size of the public-key reconstruction data alone, since no separate additional information would be required. A reduction in the size of the implicit certificate may reduce one or more of the requirements for bandwidth, computing power, and storage. Thus, at a one-time computational cost to the CA during the generation of the implicit certificate, subsequent costs associated with the use of the certificate may be reduced.

[0018] The proposed framework can be applied to the automatic renewal of certificates. The framework may also be modified for use in other cryptographic schemes, both ECC-based and non-ECC based, including digital signature protocols.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The figures of the accompanying drawings are intended to illustrate by way of example and not limitation. Like reference numbers in the figures indicate corresponding, analogous or similar elements.

[0020] Figure 1 is a simplified block diagram of an example implicit certificate scheme for a requestor, a certificate authority and a recipient;

[0021] Figure 2 is a simplified flowchart of an example method to be performed by a certificate authority for incorporating information in public-key reconstruction data of an implicit certificate;

[0022] Figure 3 is a simplified flowchart of another example method to be performed by a certificate authority for incorporating information in public-key reconstruction data of an implicit certificate;

[0023] Figure 4 is a simplified flowchart of an example method to be performed by a requestor of an implicit certificate for extracting information from public-key reconstruction data contained in the implicit certificate and for computing a public key of the requestor and a private key of the requestor;

[0024] Figure 5 is a simplified flowchart of an example method to be performed by a recipient of an implicit certificate for extracting information from public-key reconstruction data contained in the implicit certificate and for computing a public key of a requestor of the implicit certificate; and

[0025] Figure 6 is a simplified block diagram of a requestor device, a certificate authority device, and a recipient device.

DETAILED DESCRIPTION

[0026] In the following examples, it may be assumed, unless otherwise stated, that all participants in a cryptographic scheme have agreed on suitable domain parameters. For example, for a scheme instantiated using a group of points on an elliptic curve, the participants agree on the corresponding elliptic curve domain parameters $D = (p, a, b, G, n, h)$ as described above. Furthermore, in the case of certificate schemes or digital signature schemes, it may be assumed that all participants are in possession of the relevant public key of the CA or the signer, respectively. It may be assumed, unless otherwise stated, that implicit certificates are generated according to the ECQV implicit certificate scheme.

[0027] Figure 1 is a simplified block diagram of an example implicit certificate scheme involving a requestor 100 of an implicit certificate 102, a CA 104, and a recipient 114. Recipient 114 is also known as a certificate processor 114. CA 104 has a public key K_{CA} and a private key k_{CA} , where public key K_{CA} of CA 104 is equal to a product of private key k_{CA} of CA 104 and base point G , that is $K_{CA} = k_{CA}G$, where G is a base point on elliptic curve E . The generation of implicit certificate 102 may be initiated when requestor 100 sends a certificate request 106 to CA 104. First, requestor 100 generates a random or pseudo-random integer d_A in an interval $[1, n - 1]$. Integer d_A is a private value of requestor 100 that should not be disclosed to other entities. Requestor 100 then calculates a public value Q_A as a product of private value d_A and base point G , that is $Q_A = d_A G$. Requestor 100 proceeds to send request 106 for an implicit certificate to CA 104, where certificate request 106 includes public value Q_A of requestor 100 and information regarding the identity of requestor 100.

[0028] Upon receipt of certificate request 106, CA 104 proceeds to format, or encode, implicit certificate 102. CA 104 also generates an implicit signature 108 of implicit certificate 102 using private key k_{CA} of CA 104, such that implicit signature 108 can later be used by requestor 100 to compute a private key of requestor 100. For this reason, implicit signature

108 is also known as private-key reconstruction data. Implicit certificate 102 contains public-key reconstruction data 110 which may be used in conjunction with public key K_{CA} of CA 104 to calculate the public key of requestor 100. Implicit certificate 102 also contains additional information 112 which may be related to, for example, one or more of requestor 100, implicit certificate 102, or a public key of requestor 100 that is to be calculated from public-key reconstruction data 110. Following the formatting of implicit certificate 102, CA 104 sends implicit certificate 102 and implicit signature 108 to requestor 100, which may then use them to calculate a key pair consisting of the private key of requestor 100 and the public key of requestor 100. Requestor 100 may subsequently send implicit certificate 102 to recipient 114 so that recipient 114 can calculate the public key of requestor 100. Alternatively, recipient 114 may obtain implicit certificate 102 directly from CA 104 (not shown).

[0029] Figure 2 is a simplified flowchart of an example method to be performed by a CA, such as CA 104, for incorporating information in public-key reconstruction data of an implicit certificate, such as implicit certificate 102. At 200, the CA receives a request from a requestor, such as requestor 100, for an implicit certificate IC_A . At 202, the CA optionally checks the validity of the received information in the certificate request, including the identity of the requestor and public value Q_A of the requestor. If one or both of these optional verifications fails, the method may end in failure at 204. For example, if the CA determines that public value Q_A of the requestor is not a point on elliptic curve E whose elliptic curve domain parameters D have been agreed upon by the CA and the requestor, the method may end in failure at 204.

[0030] If both the identity of the requestor and public value Q_A of the requestor are successfully verified at 202 or if the optional verification is skipped, the CA proceeds to 206, where it selects information V_A to be incorporated in public-key reconstruction data B_A , where public-key reconstruction data B_A is to be part of implicit certificate IC_A . Information V_A may be related to, for example, one or more of implicit certificate IC_A , the requestor of

implicit certificate IC_A , or a public key K_A of the requestor that is to be computed from public-key reconstruction data B_A . For example, information V_A may include identity information that was received along with public value Q_A from the requestor. Information V_A may comprise a validity period of implicit certificate IC_A or a validity date of implicit certificate IC_A or both. It is expected that information V_A is from a relatively small set, for example, a set of cardinality $< 2^{32}$. In practice, the cardinality is limited by the computational capability of the CA to handle the processing required to determine public-key reconstruction data B_A that incorporates information V_A .

[0031] At 208, the CA generates a random or pseudo-random integer d_{CA} in an interval $[1, n - 1]$, where integer d_{CA} is a private value of the CA that should not be disclosed to other entities. From private value d_{CA} of the CA, the CA calculates a public value Q_{CA} that is equal to a product of private value d_{CA} of the CA and base point G , that is $Q_{CA} = d_{CA}G$, where G is the base point on elliptic curve E that was used during the calculation of public value Q_A of the requestor, as described with respect to Figure 1.

[0032] At 210, the CA calculates public-key reconstruction data B_A as a sum of public value Q_A of the requestor and public value Q_{CA} of the CA, that is $B_A = Q_A + Q_{CA}$. At 212, the CA checks whether application of a known function F to public-key reconstruction data B_A results in information V_A , that is $F(B_A) = V_A$. Numerous functions F are contemplated. As a simple example, function F could extract a subset of the bits from public-key reconstruction data B_A , such as the first 20 bits or the last 20 bits of 160-bit public-key reconstruction data B_A , for example. Alternatively, a more complicated function F could be used, such as a

decompression algorithm or a function that adds certain bits of public-key reconstruction data B_A together. Regardless of how function F is defined, it must be agreed on by all entities involved in the ECC-based protocol if information V_A is to be incorporated in public-key reconstruction data B_A and extracted from public-key reconstruction data B_A at some later point in time.

[0033] Returning to the example method illustrated in Figure 2, if the CA determines at 212 that application of function F to public-key reconstruction data B_A does not result in information V_A , that is $F(B_A) \neq V_A$, then the CA returns to 208, generating a new private value 'new d_{CA} ' and calculating a corresponding new public value Q_{CA} , that is 'new Q_{CA} ' = 'new d_{CA} ' G . Then the CA proceeds at 210 to calculate new public-key reconstruction data B_A from new public value Q_{CA} , that is 'new B_A ' = Q_A + 'new Q_{CA} ', and determines at 212 whether application of function F to new public-key reconstruction data B_A results in information V_A , that is $F(\text{'new } B_A\text{'}) = V_A$. This process of determining public-key reconstruction data B_A by generating a new private value d_{CA} and calculating a corresponding new public value Q_{CA} and new public-key reconstruction data B_A is repeated until the CA determines at 212 that information V_A can be obtained by applying function F to public-key reconstruction data B_A . Upon this determination, the CA proceeds at 214 to construct additional information ID_A , in the event that particular information V_A does not already include all the information to be included in implicit certificate IC_A . Additional information ID_A may include data that is not already included in information V_A . For

example, additional information ID_A may include information related to one or more of implicit certificate IC_A , the requestor of implicit certificate IC_A , or public key K_A of the requestor that is to be computed from public-key reconstruction data B_A . Additional information ID_A may include a validity period of implicit certificate IC_A or a validity date of implicit certificate IC_A or both.

[0034] At 216, the CA formats, or encodes, implicit certificate IC_A such that implicit certificate IC_A contains public-key reconstruction data B_A and additional information ID_A encoded in a reversible manner. For example, public-key reconstruction data B_A and additional information ID_A could be concatenated, that is $B_A || ID_A$. To ensure that the concatenation is reversible even when the concatenated values are of variable length, it is contemplated that encoding of public-key reconstruction data B_A and additional information ID_A in a reversible manner could be done using ASN.1 as described by Brown in “Standards for Efficient Cryptography SEC 1: Elliptic Curve Cryptography”, Certicom Corp., May 21, 2009. This involves the use of nested bit strings of the form TLV , where T is a short string indicating a type, L is a string indicating the length of next field V , and V is a value which can itself contain other $TLVs$. Therefore, to reversibly encode public-key reconstruction data B_A and additional information ID_A , it is contemplated that one could use one outer TLV whose tag indicates that it is a sequence of values, and two inner $TLVs$ that are included as part of the outer V field. It is primarily the length indicators that ensure the encoding is reversible.

[0035] At 218, the CA calculates an implicit signature s , for example, according to equation 1:

$$\textbf{[0036]} \quad s = \text{Hash}(IC_A)d_{CA} + k_{CA} \pmod{n} \quad (1)$$

[0037] where $Hash$ is a cryptographic hash function, such as, for example, the Secure Hash Algorithm 1 (SHA-1) or any of the SHA2 functions, for example SHA-256. Regardless of which hash function is used, it must be agreed on by all entities involved in the ECC-based protocol. Although not explicitly shown, $Hash(IC_A)$ is converted to an integer for use in equation 1.

[0038] At 220, the CA sends implicit certificate IC_A and implicit signature s to the requestor. Although not explicitly shown, the CA may make implicit certificate IC_A directly available to another entity, for example, a recipient, also known as a certificate processor. This may be accomplished, for example, by making implicit certificate IC_A available for download from a website hosted by the CA, or by broadcast transmission of implicit certificate IC_A to relevant devices.

[0039] Figure 3 is a simplified flowchart of another example method to be performed by a CA, such as CA 104, for incorporating information in public-key reconstruction data of an implicit certificate, such as implicit certificate 102. This method includes a more efficient means of searching for public-key reconstruction data that incorporates selected information V_A .

[0040] As described above with respect to Figure 2, the example method illustrated in Figure 3 includes receipt of an implicit certificate request at 200, optional verification of the requestor's identity and public value Q_A of the requestor at 202 (followed by the method ending in failure at 204 if the verification fails), selection of information V_A to be incorporated in public-key reconstruction data B_A at 206, generation of private value d_{CA} of the CA and public value Q_{CA} of the CA at 208, and calculation of public-key reconstruction data B_A at 210. However, in this method, if the CA determines at 212 that application of known function F to public-key reconstruction data B_A does not result in information V_A , that is $F(B_A) \neq V_A$,

then, rather than returning to 208 to generate a new private value d_{CA} , the CA proceeds at 311 to increment private value d_{CA} by a constant integer c , that is 'new d_{CA} ' = 'old d_{CA} ' + c . Accordingly, public-key reconstruction data B_A is incremented by the product of constant c and base point G , that is 'new B_A ' = 'old B_A ' + cG . An example for the constant c is the value one, that is $c = 1$, 'new d_{CA} ' = 'old d_{CA} ' + 1, and 'new R ' = 'old R ' + G . The CA then proceeds at 212 to check again if application of function F to new public-key reconstruction data B_A results in information V_A , that is $F(\text{'new } B_A\text{'}) = V_A$. Incrementing private value d_{CA} of the CA and public-key reconstruction data B_A has the advantage that the CA may avoid performing a separate and lengthier computation of public value Q_{CA} , which requires the use of different point multiplication in each iteration. This may reduce the amount of computation time or computation power or both that is required to determine public-key reconstruction data B_A that satisfies the requirement that application of function F to public-key reconstruction data B_A results in information V_A , that is $F(B_A) = V_A$.

[0041] Once the CA determines at 212 that application of function F to public-key reconstruction data B_A results in information V_A , that is $F(B_A) = V_A$, the CA proceeds, as illustrated in the example method of Figure 2, to construct additional information ID_A at 214, to format implicit certificate IC_A at 216, to calculate implicit signature s at 218, for example, according to equation 1, and to send implicit certificate IC_A and implicit signature s to the requestor at 220. As noted above, it is also contemplated that the CA may make implicit certificate IC_A directly available to another entity, for example, a recipient.

[0042] Figure 4 is a simplified flowchart of an example method to be performed by a requestor, such as requestor 100, of an implicit certificate, such as implicit certificate 102, for extracting information from public-key reconstruction data contained in the implicit certificate and for computing a public key of the requestor and a private key of the requestor. At 400, the requestor receives an implicit certificate IC_A and an implicit signature s from a CA, such as CA 104 in Figure 1, where implicit certificate IC_A has been formatted as described with respect to Figure 2 or Figure 3 and implicit signature s has been calculated, for example, according to equation 1. At 402, the requestor extracts public-key reconstruction data B_A and additional information ID_A from implicit certificate IC_A . This is possible because public-key reconstruction data B_A and additional information ID_A were reversibly encoded in implicit certificate IC_A during formatting by the CA as described above. Once the requestor has extracted public-key reconstruction data B_A and additional information ID_A , the requestor may optionally verify the contents of additional information ID_A at 404. If additional information ID_A cannot be successfully verified, the method may end in failure at 406. If the verification of ID_A is successful or if the optional verification is skipped, at 408 the requestor extracts information V_A from public-key reconstruction data B_A by applying the known function F to public-key reconstruction data B_A . The requestor optionally checks at 410 whether information V_A complies with certificate policy management rules known to or accessible by the requestor. If the requestor determines that information V_A does not comply with the known certificate policy management rules, the method may end in failure at 406. If the requestor determines that information V_A complies with the known certificate policy

management rules or if the optional check of information V_A is skipped, the requestor may optionally proceed to verify public-key reconstruction data B_A at 412. If public-key reconstruction data B_A cannot be successfully verified, for example, because public-key reconstruction data B_A is not a valid point on elliptic curve E , the method may end in failure at 406. However, if the verification of public-key reconstruction data B_A is successful or if the optional check of public-key reconstruction data B_A is skipped, the requestor proceeds to calculate a public key K_A of the requestor at 414 according to equation 2:

$$\text{[0043]} \quad K_A = \text{Hash}(IC_A) \cdot B_A + K_{CA} \quad (2)$$

[0044] where *Hash* is the same cryptographic hash function that was used in the calculation of implicit signature s , for example, in equation 1. As in equation 1, $\text{Hash}(IC_A)$ is converted to an integer for use in equation 2. It is assumed that the requestor is in possession of an authenticated copy of public key K_{CA} of the CA. The requestor may also calculate private key k_A of the requestor at 416, for example, according to equation 3:

$$\text{[0045]} \quad k_A = \text{Hash}(IC_A) \cdot d_A + s \pmod{n} \quad (3)$$

[0046] where *Hash* is the same cryptographic hash function that was used in the calculation of implicit signature s , for example, in equation 1 and the calculation of public key K_A of the requestor in equation 2. As in equation 1, $\text{Hash}(IC_A)$ is converted to an integer for use in equation 3. While public key K_A is shown to be computed prior to private key k_A in the example method illustrated in Figure 4, it is contemplated that the computations at 414 and 416 may be performed in a different order than that illustrated in Figure 4, while still yielding the same results. Similarly, it is contemplated that the optional verifications at 404, 410 and

412 may be performed in a different order than that illustrated in Figure 4, while still yielding the same results.

[0047] The requestor may send implicit certificate IC_A to another entity, denoted a recipient, so that the recipient can compute the requestor's public key K_A . Alternatively, the recipient may obtain implicit certificate IC_A directly from the CA. The recipient may then implicitly authenticate the requestor's public key K_A by using it, for example, in a digital signature algorithm or to encrypt information that it wants to send to the requestor.

[0048] Figure 5 is a simplified flowchart of an example method to be performed by a recipient, such as recipient 114, of an implicit certificate, such as implicit certificate 102, for extracting information from public-key reconstruction data contained in the implicit certificate and for computing a public key of a requestor of the implicit certificate. At 500, the recipient receives an implicit certificate IC_A , where implicit certificate IC_A has been formatted as described above with respect to Figure 2 or Figure 3. At 502, the recipient extracts public-key reconstruction data B_A and additional information ID_A from implicit certificate IC_A . This is possible because public-key reconstruction data B_A and additional information ID_A were reversibly encoded in implicit certificate IC_A during formatting by the CA as described above. Once the recipient has extracted public-key reconstruction data B_A and additional information ID_A , the recipient may optionally verify the contents of additional information ID_A at 504. If additional information ID_A cannot be successfully verified, the method may end in failure at 506. If the verification of additional information ID_A is successful or if the optional check of additional information ID_A is skipped, at 508 the recipient extracts information V_A from public-key reconstruction data B_A by applying the known function F to public-key

reconstruction data B_A . The recipient optionally checks at 510 whether information V_A complies with certificate policy management rules known to or accessible by the recipient. If the recipient determines that application of function F to public-key reconstruction data B_A results in information V_A that does not comply with the known certificate policy management rules, the method may end in failure at 506. If the recipient determines that information V_A complies with the known certificate policy management rules or if the optional check of information V_A is skipped, the recipient may optionally proceed to verify public-key reconstruction data B_A at 512. If public-key reconstruction data B_A cannot be successfully verified, for example, because public-key reconstruction data B_A is not a valid point on elliptic curve E , the method may end in failure at 506. However, if the verification of public-key reconstruction data B_A is successful or if the optional check of public-key reconstruction data B_A is skipped, the recipient proceeds to compute public key K_A of the requestor at 514. This may be done using equation 2, assuming that the recipient is in possession of an authenticated copy of public key K_{CA} of the CA.

[0049] It is contemplated that the optional verifications at 504, 510 and 512 may be performed in a different order than that illustrated in Figure 5, while still yielding the same results.

[0050] Various examples for **meaningful** particular information V_A have been described. Many iterations may need to be performed during generation of an implicit certificate before public-key reconstruction data is determined that satisfies the requirement that applying known function F to the public-key reconstruction data results in the particular information. However, the number of iterations may be reduced if, instead of meaningful particular information, the only requirement is that particular information V_A is a value not previously

incorporated in public-key reconstruction data of implicit certificates issued by the same CA. Such information V_A effectively serves as a certificate identifier unique in the space of implicit certificates issued by the same CA.

[0051] In an extension of the proposed framework, a CA may automatically renew an implicit certificate without receiving a renewal request. For example, if an original implicit certificate IC_A is formatted with a validity period of one year, the CA could issue a renewed implicit certificate IC_A to the requestor every year in advance of the anniversary of the initial enrollment. In this case, the CA would have close to one year to take the original certificate request and corresponding output from the original certificate fulfillment and to determine new public-key reconstruction data B_A that satisfies the requirement that application of a known function F to new public-key reconstruction data B_A results in new information V_A , that is $F(\text{'new } B_A\text{'}) = \text{'new } V_A\text{'}$, where new information V_A is or includes, for example, an updated validity date for a renewed implicit certificate IC_A . Once new public-key reconstruction data B_A is found that satisfies these requirements, the CA could store renewed implicit certificate IC_A and an associated renewed implicit signature s until the anniversary approaches, at which point the CA could send renewed implicit certificate IC_A and renewed implicit signature s to the requestor. The requestor would then proceed to compute a renewed private key k_A of the requestor corresponding to new public-key reconstruction data B_A , where new public-key reconstruction data B_A is reversibly encoded in renewed implicit certificate IC_A , as previously described.

[0052] In order for the requestor to calculate renewed private key k_A of the requestor, equation 3 requires that the requestor must have stored either an original private value d_A that it used to calculate original public value Q_A sent to the CA during its original certificate request, or an original implicit signature s corresponding to original implicit certificate IC_A . In the case that the requestor did not store original private value d_A but did store original signature s , the requestor could solve for original private value d_A by rearranging equation 1 and substituting the values of original signature s , original implicit certificate IC_A and original private key k_A . Once in possession of original private value d_A , the requestor could use renewed implicit certificate IC_A and renewed implicit signature s to compute renewed private key k_A of the requestor.

[0053] There may be cases where function F , when applied to particular public-key reconstruction data B_A , may never yield selected information V_A . In these cases a hash function could be applied to public-key reconstruction data B_A prior to applying function F . This hash function need not be the same hash function used in the ECQV scheme itself. For example, application of function F to public-key reconstruction data B_A , that is $F(B_A)$, at 212 in Figures 2 and 3, at 408 in Figure 4, and at 508 in Figure 5, could be replaced by application of function F to a hash of public-key reconstruction data B_A , that is $F(\text{Hash}(B_A))$. This would provide the CA with a new set of values for comparison with information V_A , which may improve the likelihood that a match will be found, that is $F(\text{Hash}(B_A)) = V_A$. However, it should be noted that the other entities involved in the protocol must also be aware when a hash

function is being used. Alternatively, information V_A could be selected so as to avoid the degenerate cases where application of function F never yields information V_A .

[0054] Figure 6 is a simplified block diagram of a requestor device 600, a CA device 620, and a recipient device 654.

[0055] Requestor device 600 is an example of requestor 100 and is able to perform the example method illustrated in Figure 4. Requestor device 600 comprises a processor 602 which is coupled to a memory 604 and to a communication interface 606. Requestor device 600 may contain other elements which, for clarity, are not shown in Figure 6.

[0056] CA device 620 is an example of certificate authority 104 and is able to perform one or both of the example methods illustrated in Figures 2 and 3. CA device 620 comprises a processor 622 which is coupled to a memory 624 and to a communication interface 626. CA device 620 may contain other elements which, for clarity, are not shown in Figure 6.

[0057] Recipient device 654 is an example of recipient 114 and is able to perform the example method illustrated in Figure 5. Recipient device 654 comprises a processor 656 which is coupled to a memory 658 and to a communication interface 660. Recipient device 654 may contain other elements which, for clarity, are not shown in Figure 6.

[0058] Communication interfaces 606, 626, and 660 may be wired communication interfaces or wireless communication interfaces. For example, communication interfaces 606, 626, and 660 may be Universal Serial Bus (USB) interfaces, Ethernet interfaces, Integrated Services Digital Network (ISDN) interfaces, Digital Subscriber Line (DSL) interfaces, Local Area Network (LAN) interfaces, High-Definition Multimedia (HDMI) interfaces, Digital Visual Interfaces (DVI), or Institute of Electrical and Electronics Engineers (IEEE) 1394 interfaces such as i.LINKTM, LynxSM or Firewire®. Alternatively, communication interfaces 606, 626, and 660 may be Wireless Local Area Network (WLAN) interfaces, short-range wireless communication interfaces such as Wireless Personal Area Network (WPAN) interfaces, or Wireless Wide Area Network (WWAN) interfaces.

[0059] Each of memories 604, 624, and 658 is able to store publicly-known parameters 610, including a public key K_{CA} of CA device 620 as well as elliptic curve domain

parameters D , function F , and hash function $Hash$ that have been agreed on by requestor device 600, CA device 620 and recipient device 654.

[0060] Memory 604 of requestor device 600 is able to store code 608 that, when executed by processor 602, results in the example method illustrated in Figure 4. Memory 604 may also store applications (not shown) installed in requestor device 600 to be executed by processor 602.

[0061] In addition to publicly-known parameters 610, memory 604 is also able to store a private value d_A 612, a public value Q_A 614, and a requestor identity 616 of requestor device 600. As denoted by arrow 618, public value Q_A 614 and requestor identity 616 are able to be sent to CA device 620, where they may be stored in memory 624 of CA device 620. While not explicitly shown, public value Q_A 614 and requestor identity 616 may be sent from requestor device 600 via communication interface 606 and may be received by CA device 620 via communication interface 626.

[0062] Memory 624 of CA device 620 is able to store code 628 that, when executed by processor 622, results in one or both of the example methods illustrated in Figures 2 and 3. Memory 624 may also store applications (not shown) installed in CA device 620 to be executed by processor 622.

[0063] Memory 624 is able to store a private key k_{CA} 630 of CA device 620 that corresponds to public key K_{CA} of CA device 620, as well as selected information V_A 632, a private value d_{CA} 634, and a public value Q_{CA} 636. Memory 624 is also able to store an implicit certificate I_{CA} 638 which contains reversibly-encoded public-key reconstruction data B_A 640 and additional information ID_A 642, as well as an implicit signature s 644.

[0064] As denoted by arrow 646, implicit certificate I_{CA} 638 and implicit signature s 644 are able to be sent to requestor device 600, where they may be stored in memory 604 of

requestor device 600. While not explicitly shown, implicit certificate ICA 638 and implicit signature s 644 may be sent from CA device 620 via communication interface 626 and may be received by requestor device 600 via communication interface 606.

[0065] Memory 604 of requestor device 600 is further able to store information V_A 632, a public key K_A 648 of requestor device 600 and a private key k_A 650 of requestor device 600, where these values may be determined upon receipt of implicit certificate ICA 638 and implicit signature s 644 from CA device 620.

[0066] As denoted by arrow 652, implicit certificate ICA 638 is able to be sent to recipient device 654, where it may be stored in memory 658 of recipient device 654. While not explicitly shown, implicit certificate ICA 638 may be sent from requestor device 600 via communication interface 606 and may be received by recipient device 654 via communication interface 660. Alternatively, although not explicitly shown, implicit certificate ICA 638 may be obtained by recipient device 654 directly from the CA, for example, downloaded from a website hosted by the CA.

[0067] Memory 658 of recipient device 654 is able to store code 662 that, when executed by processor 656, results in the example method illustrated in Figure 5. Memory 658 may also store applications (not shown) installed in recipient device 654 to be executed by processor 656.

[0068] Memory 658 is further able to store information V_A 632 and public key K_A 648 of requestor device 600, where these values may be determined upon receipt of implicit certificate ICA 638 from requestor device 600.

[0069] Although the subject matter has been described in language specific to structural features and/or methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above.

Rather, the specific features and acts described above are disclosed as example forms of implementing the claims.

Claims:

1. A method to be performed by a certificate authority (104,620) as part of an implicit certificate scheme, the method comprising:

receiving a certificate request (106) from a requestor (100,600);

determining a point $[B_A]$ (640) on an elliptic curve, such that application of a known function $[F]$ to the point $[B_A]$ results in particular information $[V_A]$ (632);

encoding an implicit certificate $[IC_A]$ (102,638) using the point $[B_A]$ as public-key reconstruction data $[B_A]$ (110); and

calculating an implicit signature $[s]$ (108,644) that corresponds to the implicit certificate $[IC_A]$.

2. The method as claimed in claim 1, further comprising:

sending the implicit certificate $[IC_A]$ and the implicit signature $[s]$ to the requestor for use in calculating a reconstructed private key $[k_A]$ (650) which forms a key pair with a public key $[K_A]$ (648) that can be reconstructed from the public-key reconstruction data $[B_A]$.

3. The method as claimed in claim 1, further comprising:

making the implicit certificate $[IC_A]$ available to a recipient (114,654) for use in calculating a public key $[K_A]$ (648) from the public-key reconstruction data $[B_A]$.

4. The method as claimed in claim 1, wherein the particular information $[V_A]$ is related to one or more of the requestor, the implicit certificate $[IC_A]$, and a public key $[K_A]$ (648) that can be reconstructed from the public-key reconstruction data $[B_A]$.
5. The method as claimed in claim 1, wherein the particular information $[V_A]$ comprises a validity period of the implicit certificate $[IC_A]$ or a validity date of the implicit certificate $[IC_A]$ or both.
6. The method as claimed in claim 1, wherein receiving the certificate request comprises receiving from the requestor a public value $[Q_A]$ (614) of the requestor, and wherein determining the point $[B_A]$ comprises:
 - generating a private value $[d_{CA}]$ (634) of the certificate authority;
 - multiplying the private value $[d_{CA}]$ of the certificate authority by a base point $[G]$ to obtain a public value $[Q_{CA}]$ (636) of the certificate authority;
 - calculating the public-key reconstruction data $[B_A]$ as a sum of the public value $[Q_A]$ of the requestor and the public value $[Q_{CA}]$ of the certificate authority; and
 - determining whether applying the known function $[F]$ to the public-key reconstruction data $[B_A]$ results in the particular information $[V_A]$,wherein the public value $[Q_A]$ of the requestor, the base point $[G]$, and the public value $[Q_{CA}]$ of the certificate authority are on the elliptic curve.

7. The method as claimed in claim 6, wherein in the event that applying the known function $[F]$ to the public-key reconstruction data $[B_A]$ does not result in the particular information $[V_A]$, the method further comprises:

generating a new private value $[\text{new } d_{CA}]$ of the certificate authority;

multiplying the new private value $[\text{new } d_{CA}]$ of the certificate authority by the base point $[G]$ to obtain a new public value $[\text{new } Q_{CA}]$ of the certificate authority;

calculating new public-key reconstruction data $[\text{new } B_A]$ as a sum of the public value $[Q_A]$ of the requestor and the new public value $[\text{new } Q_{CA}]$ of the certificate authority;
and

determining whether applying the known function $[F]$ to the new public-key reconstruction data $[\text{new } B_A]$ results in the particular information $[V_A]$,

wherein the new public value $[\text{new } Q_{CA}]$ of the certificate authority and the new public-key reconstruction data $[\text{new } B_A]$ are on the elliptic curve.

8. The method as claimed in claim 6, wherein in the event that applying the known function $[F]$ to the public-key reconstruction data $[B_A]$ does not result in the particular information $[V_A]$, the method further comprises:

calculating an incremented private value $[d_{CA} + c]$ of the certificate authority as a sum of the private value $[d_{CA}]$ of the certificate authority and a constant integer $[c]$;

calculating incremented public-key reconstruction data $[B_A + cG]$ as a sum of the public-key reconstruction data $[B_A]$ and a product of the constant integer $[c]$ and the

base point $[G]$, wherein the incremented public-key reconstruction data $[B_A + cG]$ is on the elliptic curve; and

determining whether applying the known function $[F]$ to the incremented public-key reconstruction data $[B_A + cG]$ results in the particular information $[V_A]$.

9. A method to be performed by a requestor (100,600) as part of an implicit certificate scheme, the method comprising:

sending a certificate request (106) to a certificate authority (104,620);

receiving from the certificate authority an implicit certificate $[IC_A]$ (102,638) from which public-key reconstruction data $[B_A]$ is recoverable, wherein the public-key reconstruction data $[B_A]$ is on an elliptic curve and can be used to reconstruct a public key $[K_A]$ (648);

receiving from the certificate authority an implicit signature $[s]$ (108,644) that corresponds to the implicit certificate $[IC_A]$;

recovering the public-key reconstruction data $[B_A]$ from the implicit certificate $[IC_A]$; and

extracting information $[V_A]$ from the public-key reconstruction data $[B_A]$ by applying a known function $[F]$ to the public-key reconstruction data $[B_A]$.

10. The method as claimed in claim 9, wherein the extracted information $[V_A]$ is related to one or more of the requestor, the reconstructed public key $[K_A]$, and the implicit certificate $[IC_A]$.

11. The method as claimed in claim 9, wherein the extracted information $[V_A]$ comprises a validity period of the implicit certificate $[IC_A]$ or a validity date of the implicit certificate $[IC_A]$ or both.
12. The method as claimed in claim 9, further comprising:
- generating a private value $[d_A]$ of the requestor; and
 - calculating a public value $[Q_A]$ of the requestor as a product of the private value $[d_A]$ of the requestor and a base point $[G]$ on the elliptic curve,
 - wherein the public value $[Q_A]$ of the requestor is on the elliptic curve, and
 - wherein sending the certificate request comprises sending the public value $[Q_A]$ of the requestor.
13. The method as claimed in claim 12, the method further comprising:
- calculating the reconstructed public key $[K_A]$ from the implicit certificate $[IC_A]$ and from a public key of the CA $[K_{CA}]$, and
 - calculating a reconstructed private key $[k_A]$ from the implicit certificate $[IC_A]$, from the implicit signature $[s]$, and from the private value $[d_A]$ of the requestor,
 - wherein the reconstructed private key $[k_A]$ forms a key pair with the reconstructed public key $[K_A]$.

14. The method as claimed in claim 9, the method further comprising:

checking whether the extracted information $[V_A]$ complies with certificate policy management rules accessible by the requestor.

15. A method to be performed by a recipient (114,654) as part of an implicit certificate scheme, the method comprising:

receiving an implicit certificate $[IC_A]$ (102,638);

recovering public-key reconstruction data $[B_A]$ (110) from the implicit certificate $[IC_A]$, wherein the public-key reconstruction data $[B_A]$ is on an elliptic curve; and

extracting information $[V_A]$ (632) from the public-key reconstruction data $[B_A]$ by applying a known function $[F]$ to the public-key reconstruction data $[B_A]$.

16. The method as claimed in claim 15, wherein the extracted information $[V_A]$ is related to one or more of the implicit certificate $[IC_A]$, a requestor (100,600) of the implicit certificate $[IC_A]$, and a public key $[K_A]$ (648) that can be reconstructed from public-key reconstruction data $[B_A]$.

17. The method as claimed in claim 15, wherein the extracted information $[V_A]$ comprises a validity period of the implicit certificate $[IC_A]$ or a validity date of the implicit certificate $[IC_A]$ or both.

18. The method as claimed in claim 15, the method further comprising:
- calculating the reconstructed public key $[K_A]$ from the implicit certificate $[IC_A]$ and from a public key of a certificate authority $[K_{CA}]$; and
 - implicitly authenticating the reconstructed public key $[K_A]$ by using the reconstructed public key $[K_A]$ during communication with a requestor of the implicit certificate $[IC_A]$.
19. The method as claimed in claim 15, the method further comprising:
- checking whether the extracted information $[V_A]$ complies with certificate policy management rules accessible by the recipient.
20. A certificate authority device (104,620) for use in an implicit certificate scheme, the device comprising:
- a processor (622);
 - a communication interface (626) able to receive a certificate request (106) from a requestor device (100,600); and
 - a memory (624) storing code (628) which, when executed by the processor, results in the method of any one of claims 1 to 8.
21. A system for use in an implicit certificate generation scheme, the system comprising:
- a requestor device (100,600) to generate a certificate request (106); and
 - a certificate authority device (104,620) to perform the method of any one of claims 1 to 8.
22. A requestor device (100,600) for use in an implicit certificate scheme, the device comprising:
- a processor (602);

a communication interface (606) able to send a certificate request (106) to a certificate authority device (104,620); and

a memory (604) storing code (608) which, when executed by the processor, results in the method of any one of claims 9 to 14.

23. A system for use in an implicit certificate generation scheme, the system comprising:
- a requestor device (100,600) to perform the method of any one of claims 9 to 14; and
 - a certificate authority device (104,620) able to receive the certificate request (106) and to send to the requestor device the implicit certificate $[IC_A]$ (102,638) and the implicit signature $[s]$ (108,644).
24. A recipient device (114,654) for use in an implicit certificate scheme, the device comprising:
- a processor (656);
 - a communication interface (660) able to receive an implicit certificate $[IC_A]$ (102,638); and
 - a memory (658) storing code (662) which, when executed by the processor, results in the method of any one of claims 15 to 19.

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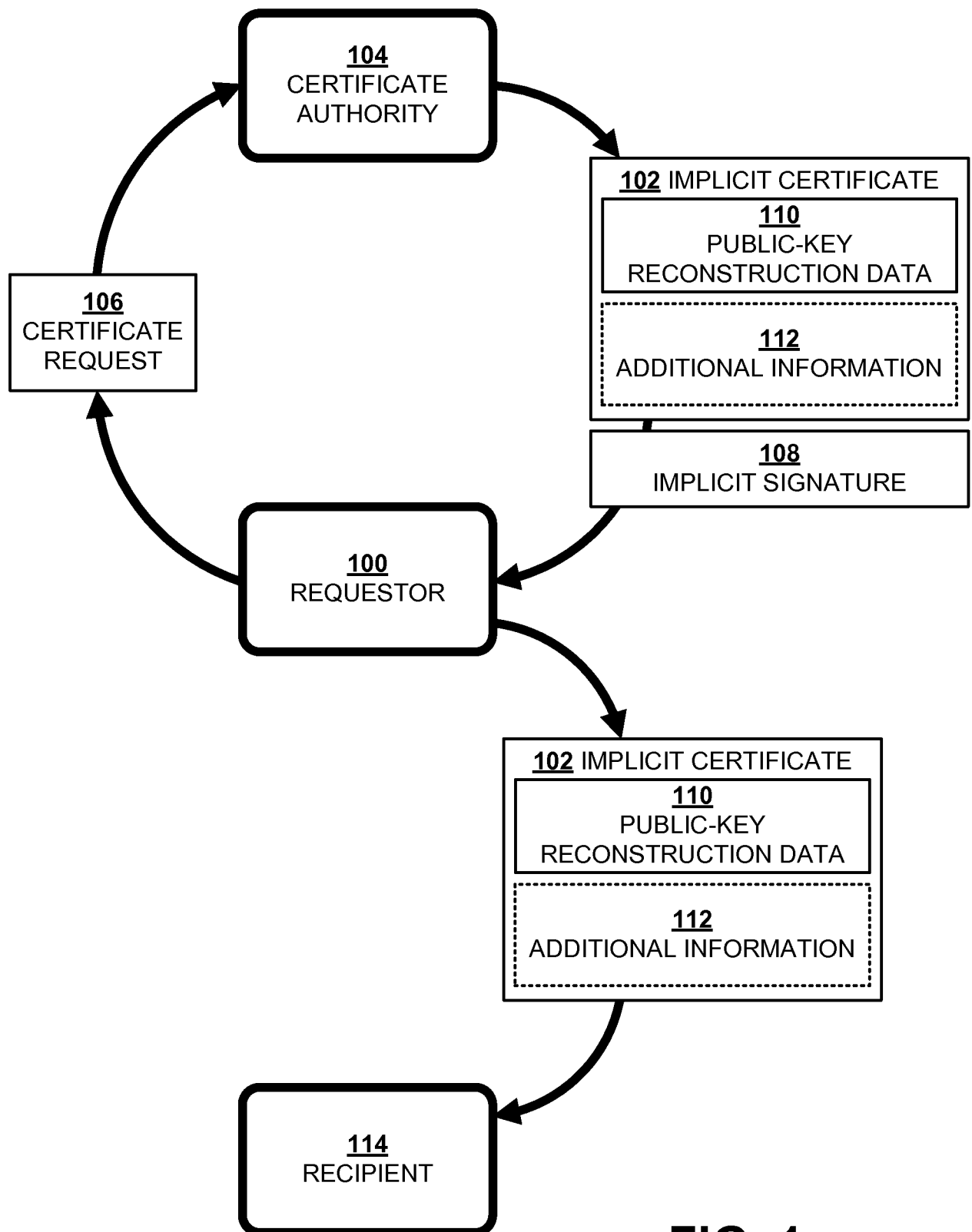
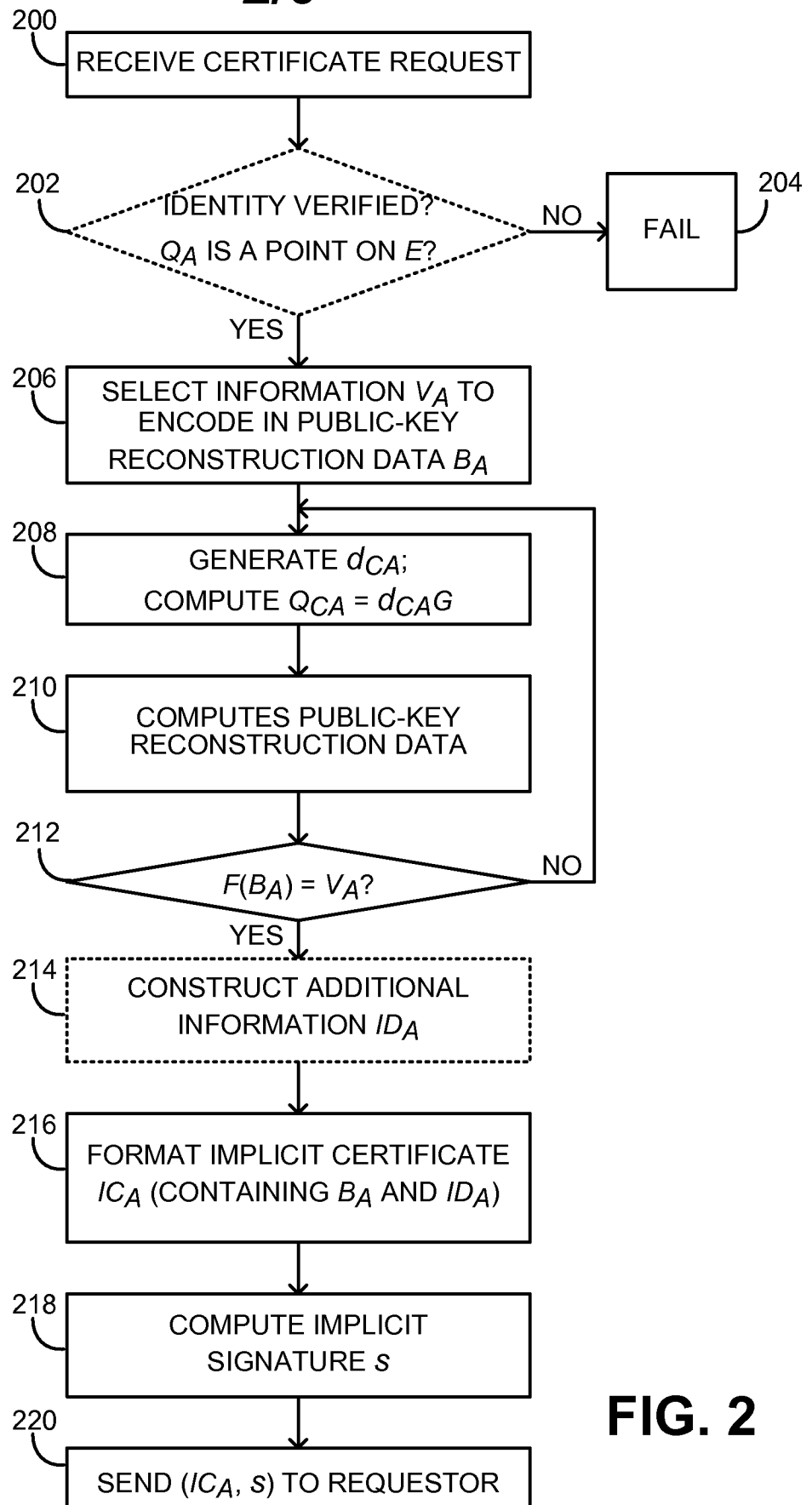
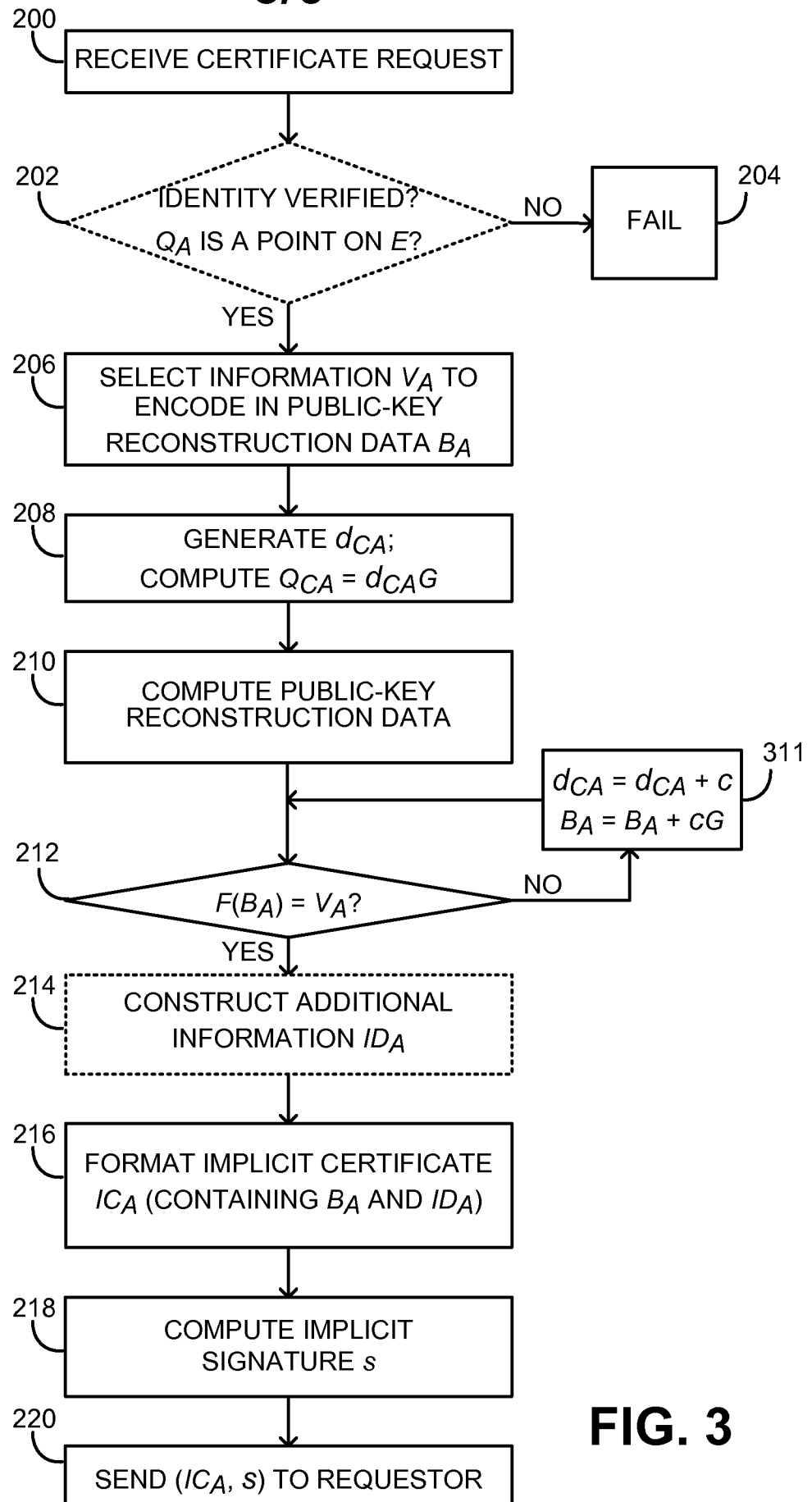


FIG. 1

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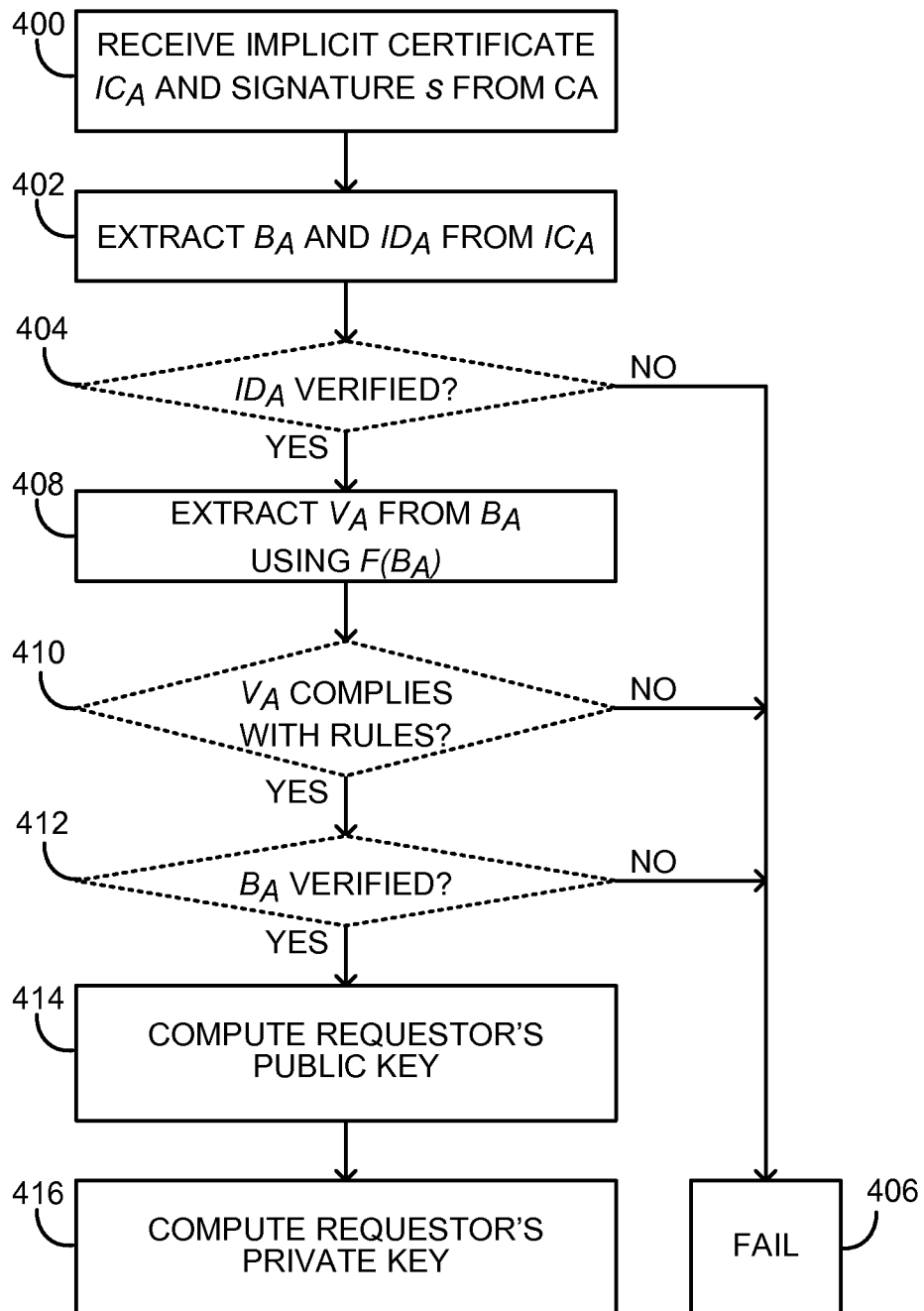


FIG. 4

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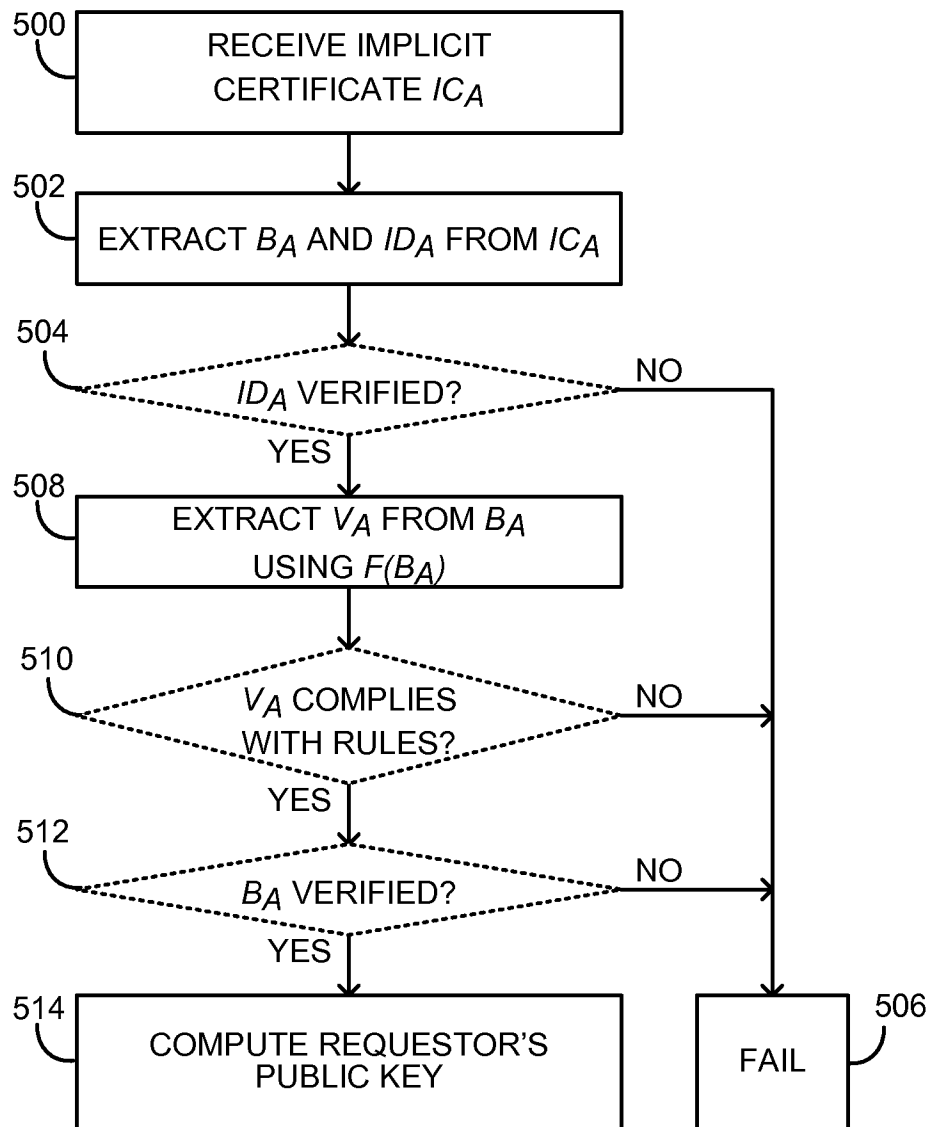


FIG. 5

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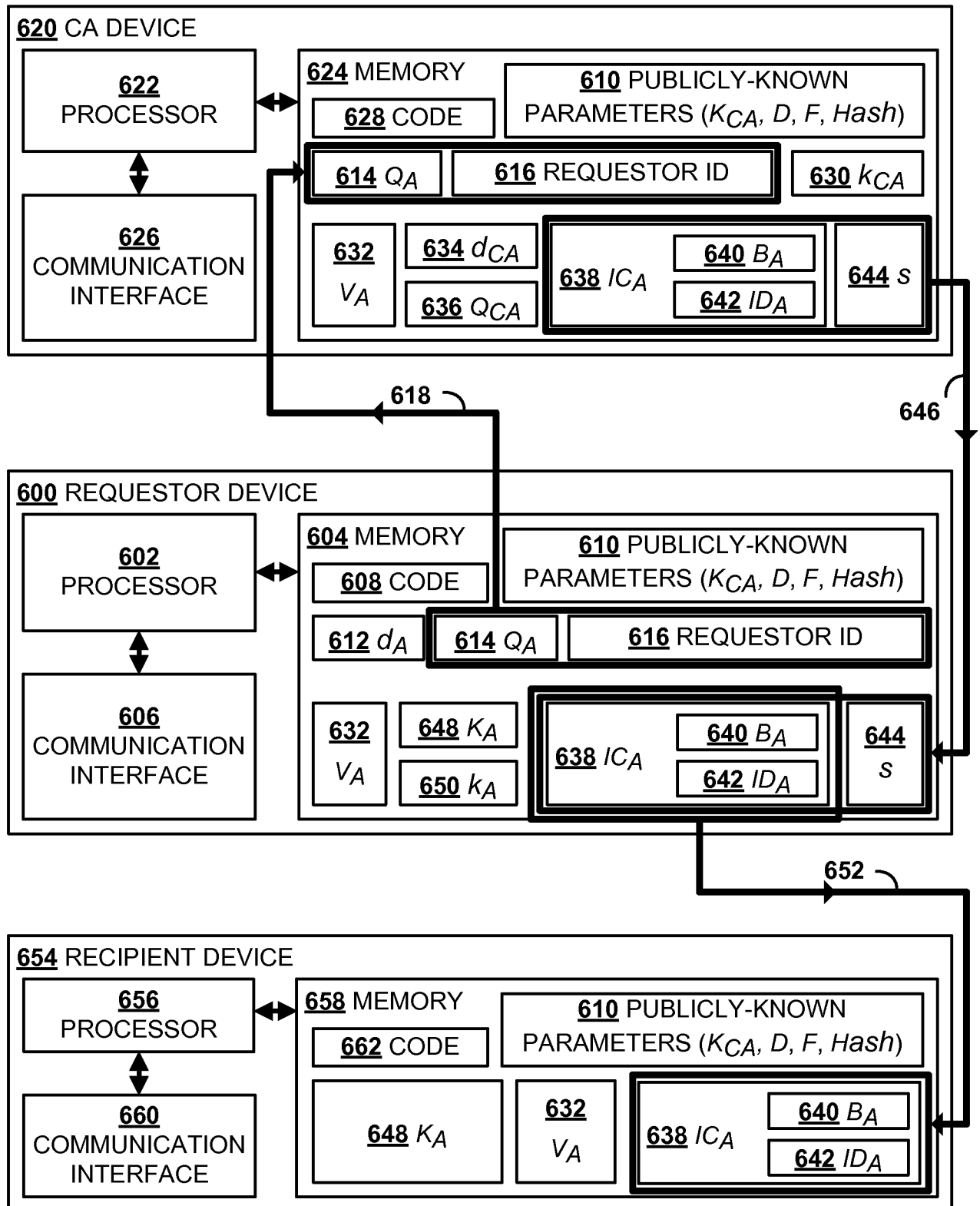


FIG. 6