NIST Internal Report
NIST IR 8450 ipd

Overview and Considerations of Access Control Based on Attribute Encryption

Initial Public Draft

Vincent C. Hu

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8450.ipd

NATIONAL INSTITUTE OF
STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

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May 2023

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NIST Technical Series Policies
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NIST Technical Series Publication Identifier Syntax

Publication History
Approved by the NIST Editorial Review Board on YYYY-MM-DD [Will be added upon final publication]

How to Cite this NIST Technical Series Publication:
Hu V (2023) Overview and Considerations of Access Control Based on Attribute Encryption. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Interagency or Internal Report (IR) 8450 ipd. https://doi.org/10.6028/NIST.IR.8450.ipd

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Public Comment Period
May 9, 2023 – June 23, 2023

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Abstract

Encryption technology can be incorporated into access control mechanisms based on user identities, user attributes, or resource attributes. Traditional public-key encryption requires different data to have different keys that can be distributed to users who satisfy perspective access control policies along with the encrypted version of the data. However, some distributed or pervasive system environments wish to avoid the public-key encryption's all-or-nothing data access limitation when considering their performance requirements. Attribute-based encryption incorporates access control policies and attributes with encryption and decryption functions and a one-to-many authorization scheme that requires fewer keys than public-key encryption. It also utilizes collusion-resistance, which provides a more efficient and flexible attribute-based access control mechanism that supports high-performance systems (e.g., cloud, IoT, disrupt-tolerant networks, wireless sensor networks, mobile ad-hoc networks, and public search service systems).

Keywords

access control; attribute-based access control; attribute-based encryption; authorization; encryptions; identity-based encryption; public-key encryption.

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Acknowledgments

The author would like to express his thanks to Lily Chen, Isabel Van Wyk, and Jim Foti of NIST for their reviews of both the public comment version as well as the final publication.

Executive Summary

Traditional public-key encryption (PKE) requires different data to have different keys that can be distributed to users who satisfy access control policies along with the encrypted version of the data. With user-specific keys, communication complexity is linear to the number of users, and pre-distributed keys are neither bound to the attributes of users and data nor to the respective access control policy. If access policies and/or attributes change dynamically (especially in real time), keys need to change as well, which could cause inefficient performance in the system. Combining cryptography with access control mechanisms can avoid the PKE's all-or-nothing limitation of keys and improve performance. Encryption technology that is typically used for key exchange, data signature, and certification can be incorporated into access control mechanisms based on user identities, user attributes, and resource attributes.

Attribute-based encryption (ABE) incorporates access control policies and attributes into encryption and decryption functions for public-key cryptography protocols through broadcasting. Fewer keys are used for ABE than for traditional PKE, which allows it to be an efficient and flexible attribute-based access control method.

The main features of ABE access control include:

- One-to-many authorization scheme
- Fine-grained access control based on user (subject) or resource (object) attributes
- Message sending without obtaining public key certificates from public key infrastructure
- Data decryption without evaluating permissions from access control policy
- Collusion-resistance so that a user who holds multiple keys cannot combine different keys to access a resource that is only allowed by one key

The fine-grained, efficient, and collusion-resistant features of ABE support the physical resources and performance demands of systems like the cloud, IoT, disrupt-tolerant networks, wireless sensor networks, mobile ad hoc networks, and public search service systems.

1. Introduction

Traditional public-key encryption (PKE) requires different data to have different keys that – along with the encrypted version of the data – can be distributed to users who satisfy access control policies. With user-specific keys, the communication complexity is linear to the number of users, and pre-distributed keys are neither bound to the attributes of users and data nor to the respective access control policy. Therefore, if access policies and/or attributes change dynamically (especially in real time), then keys need to change as well, which could cause the system's performance to become inefficient [GOLIC]. Combining cryptography with access control mechanisms can help avoid the PKE's all-or-nothing limitation of keys and lead to more efficient performance. To that end, encryption technology that is typically used for key exchange, data signature, and certification can be incorporated into access control mechanisms that are based on user identities, user attributes, and resource attributes.

Attribute-based encryption (ABE) [GPSW] incorporates access control policies and attributes into encryption and decryption functions for public-key cryptography protocols through broadcasting. ABE encrypts only once by using a public key according to attributes associated with the access control policy. Only users hold the correct private decryption keys, which satisfies the access policies for decrypting data. ABE's fine-grained access control mechanism is based on user (subject) attributes or data (resource) attributes. Thus, the size of ABE encrypted data and the resulting communication complexity for key distribution are linear in the number of attributes, not users. Broadcasting enables ABE to utilize fewer keys than traditional PKE schemes, which allows it to be an efficient and flexible attribute-based access control method.

The main features of ABE access control include:

- One-to-many authorization scheme
- Fine-grained access control based on user (subject) attributes or resource (object) attributes
- Message sending without obtaining public key certificates from public key infrastructure
- Data decryption without evaluating permissions from access control policy
- Collusion-resistance so that a user who holds multiple keys cannot combine different keys to access data that is only allowed by one key

These fine-grained, efficient, and collusion-resistant features support the physical resources and performance demands of systems like the cloud, the Internet of Things (IoT), disrupt-tolerant networks, wireless sensor networks, mobile ad hoc networks, and public search service systems [ELT, SW].

This document is organized as follows:

- Section 1 is the introduction.
- Section 2 provides an overview of the fundamental theories the ABE is built on, including elliptic-curve cryptography, bilinear pairing, and bilinear pairing for elliptic curve cryptography.
- Section 3 introduces identity-based encryption (IBE).

- Section 4 illustrates ABE algorithms of CP-ABE and KP-ABE.
- Section 5 describes considerations for applications of ABE from the perspectives of security, performance, access control policies, and support models.
- Section 6 is the conclusion.

2. Fundamental Theories

The underlying function of ABE is primarily based on public-private key cryptography calculated in bilinear pairing on elliptic curve groups. This section outlines fundamental theories of elliptic curve, elliptic-curve cryptography, bilinear group, bilinear pairing, and elliptic-curve cryptography for ABE.

2.1. Elliptic Curve

An elliptic curve is so named for being described by cubic equations (used for calculating the circumference of an ellipse), which is of the form $y^2 = x^3 + ax + b$ ($y^2 + axy + by = x^3 + cx^2 + dx + e$), where all the coefficients are real numbers that satisfy some simple conditions [ROBI, SP800-186]. However, elliptic curve is not an ellipse but rather a cubic (x^3) formed by quadratic curves. Basic specifications for elliptic curve are:

1. Single elliptic curve point at infinity – or zero point – are denoted by "0," which does not satisfy an elliptic curve equation but is needed for addition as the additive identity, $0 = -0$. For any point P on an elliptic curve, $P + 0 = P$. All vertical lines intersect the curve at infinity (0), and if three points on an elliptic curve lie on a straight line, their sum is 0.
2. The negative of a point P is the point with the same x coordinate but the negative of the y coordinate of the elliptic curve's x-y coordinate. That is, if $P = (x, y)$, then $-P = (x, -y)$, and these two points can be joined by a vertical line such that $P + (-P) = P - P = 0$, a point adds negative of itself will become an infinity point (as shown in Figure 1). Any non-vertical line will intersect the curve in three places at most [MATA].

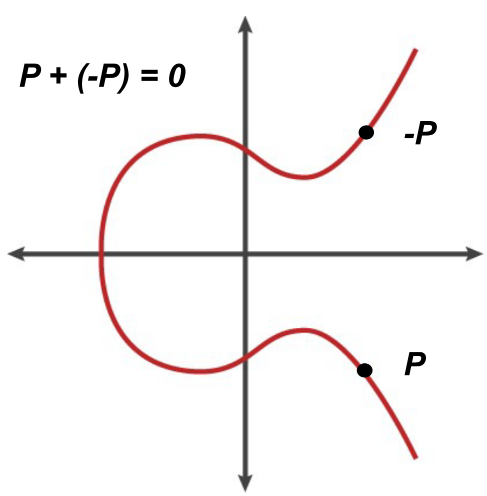

Fig. 1. $P + (-P) = P - P = 0$ in an elliptic curve

3. Add distinct points P and Q in elliptic curve, if $P \neq 0$ and $P \neq Q$ (as shown in Figure 2), where $P = (x_P, y_P)$, $Q = (x_Q, y_Q)$. If $R = P + Q = (x_R, y_R)$, then $x_R = s^2 - x_P - x_Q$ and $y_R = -y_p + s(x_P - x_R)$, where $s = (y_P - y_Q)/(x_P - x_Q)$.

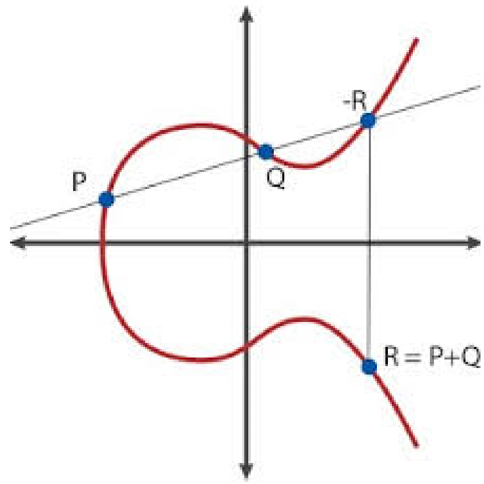

Fig. 2. *P* + *Q* in an elliptic curve

4. Doubling a point (also called *dot* function) P ($P + P = 2P$) uses P's tangent line to find the second point in the curve, which will generate a new point $-R$ and reflect $-R$ from x axis to give a new point R, such that from 3 above, if $y_P \neq 0$, $2P = R$ then replaces the Q with P and replaces s with $s = (3x_P^2 + a)/ (2y_P)$ for the elliptic curve: $y^2 = x^3 + ax + b$. Multiplying (also called dot, map, reflect) n (an integer) to a point P, $X = nP$ means $P + P + \ldots + P$ (n times) , the nP can be calculated by adding a doubling operation combined. For example $5P$ = Double(Double P) + P (i.e., $2^2+1= 5$). Note that for an elliptic curve point P, two integers n and m, $m(n(P) = n(mP)$, which is the same as the operation in a finite field $(g^y)^x = (g^x)^y$, where g is an element in a finite field and x, y are integers.

5. Order of a point P on the elliptic curve is defined to be the smallest integer n such that $nP = 0$.

6. Elliptic curve cryptography (ECC) uses elliptic curves over a finite field. F_z: $\{0 \ldots z\text{-}1\}$ is a set of points (x, y) that satisfy $y^2 = x^3 + ax + b \bmod z$, where z is a prime number > 3, and $a, b, x, y \in F_z$. For example, an elliptic curve $y^2 = x^3 + 7 \bmod 11$, when $x = 1$, $y^2 = 8 \bmod 11$, but there is no real number y satisfy $y^2 = 8 \bmod 11$. When $x = 2$, $y^2 = (8 + 7) \bmod 11 = 4 \bmod 11$, $y = 2$, or y = 9 can satisfy the formula, so points (2, 2) and (2, 9) are in the elliptic curve. When $x = 3$: $y^2 = (27 + 7) \bmod 11 = 1 \bmod 11$, $y = 1$ or 10. Continually, we conclude that points (2, 2), (2, 9), (3,1), (3, 10), (4, 4), (4, 7), (5, 0), (6, 5), (6, 6), (7, 3), and (7, 9) are in the elliptic curve over the finite field defined by mod 11.

2.2. Elliptic Curve Cryptography

Elliptic curve cryptography (ECC) [SP800-56A, FIPS186-5] was invented by Neal Koblitz and Victor Miller in 1985 [MMSC] and standardized in IEEE P1363a. The primary advantage of using elliptic curve-based cryptography is that ECC has shorter key/parameter than RSA's PKE to achieve the same security strength. [MY]. This property addresses performance issues for systems such as wireless communication devices, smart cards, web servers, and applications that need to handle many encryption sessions at the same time. These systems need security but lack the power, storage, or computational capability required for RSA's PKE cryptographic scheme. For example, Bitcoin and Ethereum use *secp256k1* elliptic curve to generate private and public key pairs [MOBI] for their blockchain implementations. Discrete logarithm problem (DLP) (i.e., given two points, P and Q on an elliptic curve, find an integer a such that $Q = aP$) on an elliptic curve is hard. However, ECC is more difficult to explain when compared to traditional RSA's PKE cryptographic scheme [ROBI]. As ECC gains popularity, more applications are using it, such as Internet Key Exchange (IKE), TLS, Tor, iMessage, Bitcoin, and Ethereum [LXYS].

The international consortium Standards for Efficient Cryptography Group (SECG) [DANI] developed commercial standards for efficient and interoperable ECC. SECG published a document with a recommend set of parameters refereed by the tuple (p, a, b, G, n, h) called Elliptic Curve Domain Parameters to describe an elliptic curve used for ECC, where p is a prime number for defining the finite field such that $F_p = \{0 \ldots p\text{-}1\}$, a and b (are usually restricted by $4a^3 + 27 + b^2 \neq 0$) are the coefficients of the elliptic curve equation $y^2 = x^3 + ax + b$. [SP800-186] G is the generator point. n is the order of the G generator (base) point (also called n torsion point), which determines the maximum value that can be turned into private key (ranging from 1 to n -1). h equals N/n called *cofactor* such that N is the order of the elliptic curve (the number of points in the elliptic curve). For example, the finite field F_{37} with $p = 37$ for the elliptic curve: $y^2 = x^3 - x + 3 \bmod 37$ ($a = -1$, $b = 3$) has order $N = 42$. For $n = 7 \in$ factors of N in {1, 2, 3, 6, 7, 14, 21, 42}, we can decide the point $P = (2, 3)$ is the base point G because $P \neq 0$, $2P \neq 0$, $3P \neq 0$, $6P \neq 0$, but $7P = 0$. According to Lagrange's theorem, the order of subgroup (generated by G) is a factor of N. That is, $N = nh$. For any point P in the elliptic curve, $NP = 0$ (i.e., $n(hP) = 0$). Elliptic curves defined by parameter sets have been given IDs in the standards for easier identification. For example, s*ecp256k1* is EC $y^2 = x^3 + 7$ (used by Bitcoin or Ethereum) [SP800-186, MOBI].

For cryptographic usage, the elliptic curves are selected with a subgroup generated by the generator point G such that the order is a prime and large enough for targeted security strength. The steps are:

1. Select an elliptic curve pseudo randomly ((Note that ECC standards use recommended curves with already defined subgroup and generator in C.3.1. in [SP800-186]).
2. Calculate the order N of the elliptic curve. (Schoof's algorithm [SCHOOF] can be applied to find N, but it does not work for finding the order of a subgroup generated by a point.)
3. If N has a prime factor n, which is large enough to satisfy the required security strength, go step 4. Otherwise, go to step 1.
4. Compute the cofactor $h = N/n$.
5. Choose a random point P as a candidate generator G on the curve.
6. Compute $G = hP$.
7. If G is 0 (i.e., the subgroup has order 1), then go back to step 4. Otherwise, G is the generator (of a subgroup) with order n and cofactor h.

Note that this algorithm only works if n is a prime. If n were not a prime, then the order of G could be one of the divisors of n [CORB].

In ECC, a point $X = nG$ where n is an integer and G is the generator is used for the public key, and n is used as the private key. For example, the message from the sender to the receiver with the ciphertext $C_m = \{KG, M + KP_{receiver}\}$ can be decrypted by function *Decrypt* (C_m): $M + KP_{receiver} - S_{receiver}(KG) = M + K(S_{receiver}G) - S_{receiver}(KG) = M$, where M is the message converted to an elliptic point, K is a random number, KG is a point in the elliptic curve, which can be known by everyone sent through non-encrypted channel, $P_{receiver}$ is the receiver's public key, $S_{receiver}$ is the receiver's private key such that $P_{receiver} = S_{receiver}G$, and "+" is elliptic curve points addition [ROBI]. ECC can also be applied to digital signature, for instance, The Elliptic Curve Digital Signature Algorithm (ECDSA): Assume that the private key $Pr = d$ is an integer. The public key $Q = kG$ is an elliptic curve point. To sign a message m, compute $e = H(m)$, where H is a hash function and assume e is an integer such that $1< e < n$. Randomly select an integer k, $1 < k < n$ to compute $R= kG = (x_R, y_R)$, then convert finite field element x_R to an integer r, such that $1< r < n$. Compute $s = k^{-1}(e + r \cdot d) \bmod n$. The signature of m is (r, s). To verify the signature $Sig(m) = (r, s)$, a verifier computes $e = H(m)$. With the signature (r, s) and e, the verifier computes two values $u = e \cdot s^{-1} \bmod n$ and $v = r \cdot s^{-1} \bmod n$, with u and v, computes an elliptic point $R_1 = uG + vQ = (x_{R'}, y_{R'})$. After converting finite field element $x_{R'}$ to an integer r_1, such that $1< r_1 < n$. If $r = r_1$, then (r, s) is a valid signature, otherwise, it is not a valid signature. As shown is the following steps:

Parameters

G: a generator of the elliptic curve group over a finite field with order n, where n is a prime.

d: private key, an integer, $1< d <n$,

Q: public key, $Q = dG = G + G +\ldots+ G$ (d times)

Message to be signed

m: message to be signed.

Signing

1. Randomly select an integer k, $1 < k < n$, compute $R= kG = (x_R, y_R)$
2. Convert finite field element x_R to an integer r, such that $1< r < n$
3. Compute $e = H(m)$, Here assumes that $e = H(m)$ is an integer $1< e < n$
4. Compute $s = k^{-1}(e + r \cdot d) \bmod n$
5. Output (r, s) as the signature of m.

Verifying

1. Compute $e = H(m)$
2. Compute $u = e \cdot s^{-1} \bmod n$ and $v = r \cdot s^{-1} \bmod n$
3. Compute $R_1 = uG + vQ = (x_{R'}, y_{R'})$
4. Convert finite field element $x_{R'}$ to an integer r_1, such that $1< r_1 < n$
5. If $r = r_1$, then (r, s) is a valid signature.

2.3. Bilinear Pair Mapping

Based on elliptic curve, Bilinear Pairing Cryptography can be used for such as New Signature [ST], Identity-based encryption (IBE) [BF], and Attribute-based Encryption (ABE) – by applying bilinear pair mapping operations (i.e., bilinear pairing) on groups. For the consistency of notation, from this point of document, we will use G to denote a group and elements in a group will be denoted by letters in lower case. For instance, g to indicate a generator of G. In general, a group is defined by a set of elements and an operation on the group. In Section 2.2, we introduced group consisting of points on an elliptic curve with operation addition "+". A prime order subgroup with generator g is a cyclic group. That is, the group generated by g is $\{0, g, 2g, \ldots, (n\text{-}1)g\}$, where n is the order of G. It can define a mapping from integer group $\{0, 1, 2, \ldots, n\text{-}1\}$ to the cyclic group such that $f(x) = xg$. such that $f(x + y) = xg + yg$. For an integer n, a group is called a cyclic group of order n, if the group elements can be represented as $\{0, g, 2g, \ldots, (n\text{-}1)g\}$ and ng =0, where g is a generator. G.

Let G_1 and G_2 be cyclic groups of the same order (e.g., G_1 and G_2 are cyclic additive groups generated by g whose order is a prime n). The bilinear pairing is a computable function e: $G_1 \times G_2 \rightarrow G_T$ that associates pairs of elements from G_1 and G_2 with elements in groups G_T, which is a group that contains the nth roots of unity [WF]. If (u, v) is a pair of elements such that $u \in G_1$, $v \in G_2$ are points of G_1 and G_2, respectively, then bilinear pairing function e takes u and v to produce a value in Group G_T. Bilinear pairing has the following properties when $a, b, c, d \in$ Z, and $u \in G_1$, $v \in G_2$, w is an element of G_1 or G_2:

- Computing $e(u, v)$ is efficient.
- $e(u, v)^a = e(u^a, v) = e(u, v^a)$
- $e(u^a, v^b)\, e(u^c, v^d) = e(u, v)^{ab+cd}$ [QIAU]
- $e(u + w, v) = e(u, v)e(w, v)$
- $e(u, w + v) = e(u, w)e(u, v)$
- $e(au, v) = e(u, av) = e(u, v)^a$ [HUBWIZ]
- $e(au, bv) = e(abu, v)$
- $e(\text{-}u, v) = e(u, v)^{-1} = e(u, \text{-}v)$
- $e(uw, v) = e(u, v)e(w, v)$
- The mapping can also be $G_1 \times G_1 \rightarrow G_T$. In such cases, a pairing is called Symmetric: $e(u, v) = e(v, u)$ for all u, v
- $e(u^a, v^b) = e(u^b, v^a) = e(au, bv) = \mathrm{e}(av, bu) = e(bu, av) = e(u, v)^{ab}$ when $G_1 = G_2$, and the mapping is symmetric [BETH]
- Non-degenerate property $e(u, v) \neq$ identity for some u, v, which ensures that if non-identical elements are selected for e, then the result of the pairing function will not be the identity of the target group. For example, assume 0 is the identity, then $e(u, v) = 0$ for all points v if and only if $u = 0$, and $e(u, v) = 0$ for all points u if and only if $v = 0$. Note that a degenerate property maps everything to the identity 0, that is $\exists\, u \neq 0$, $v \neq 0$, $e(u, v) = 0$.

- If $e(u, u)^k = 1$, then k is either 0 or a multiple of the order of the group when $G_1 = G_2$, and the mapping is symmetric [HUBWIZ].
- Skew-symmetric: $e(u, v) = -e(v, u)$ when $G_1 = G_2$.

2.4. Bilinear Paring for Cryptography

Pairing-based cryptography [MD] applies bilinear pairing, which establishes the relationship between cryptographic groups for solving Decisional Diffie Hellman problems. Weil and Tate pairings [MEFF] were first used in an effort to break ECC. The idea was to reduce the discrete logarithm problem in elliptic curves to a discrete logarithm problem in finite fields (called a MOV reduction) [BETH]. Bilinear paring for ECC is based on the properties that add, double, and multiply (Double means adding the same element, multiply with an integer k means adding the same element k times) elliptic curve points to form an abelian group such that the bilinear pairing e: $G_1 \times G_2 \rightarrow G_T$ is defined by G_1, G_2 are subgroups of points on elliptic curves over a prime field F_p, and G_T is a subgroup of the multiplicative group of a finite field that contains the nth (n is the order or the number of points in the elliptic curve) of unity in a prime field (usually 12 degrees of extension[1] of a prime field). These values are not points. G_1, G_2, and G_T are all isomorphic to one another since they have the same order and are cyclic [BUTE, MPPRRC, IRON]. The bilinear pairing functions have the same properties as described in Section 2.3.

For this example, it is assumed that G_1 and G_2 are elliptic curve groups. But the notations are different from the curves. It uses g_1 as a point. It should be clear that private keys are integers. Message M must be an element in G_T. By the way, here it is assumed that the operation in G_1 and G_2 are "addition" and in G_T "multiplication".

For public-key encryption, an EC key pair used for bilinear pairing is public key (PK) = private key (SK)g_1 , an integer, which means that the public key is just the private key times a fixed generator point g_1 in G_1. For example:

1. *Alice* generates a key pair (SK_A, PK_A). *Bob* generates (SK_B, PK_B), and both public keys are made available to public.
2. *Alice* can encrypt a message M to *Bob* by computing $Me(PK_B, SK_A g_2)$, where g_2 is a generator point in G_2. Note that $Me(PK_B, SK_A g_2) = Me(SK_B g_1, SK_A g_2) = M\, e(SK_A g_1, SK_B g_2) = Me(PK_A, SK_B g_2)$.
3. *Bob* can recover M by computing $Me(PK_A, SK_B g_2)\, e(PK_A, -SK_B g_2) = M\, e(PK_A, (SK_B - SK_B) g_2) = Me(PK_A, 0) = M.$

Note that M must be an element in G_T. And assumed that the operation in G_1 and G_2 are addition and G_T is multiplication.

Bilinear pairing also works for message signatures. For example, *Alex* signs her message and sends it to *Bob* such that *Alex* generates SKg = public key PK, signature $C = SKH(M)$, where SK is *Alex*'s secret key, g is the generator of elliptic curve that publicly known, M is the message *Alex* signed, and H is a hash function for hashing message M to another point in the elliptic curve. Bob receives C, PK, $H(M)$ and then calculates to check if the pair mapping e of g and C

[1] Numbers that consist of 12 different values between 0 and prime – 1 equivalent security of the degree extension of a 256-bit prime field are under 100 bits. [IRON]

equal the pair mapping of PK and $H(M)$ for Alex's signature of M: $e(g, C) = e(PK, H(M)) = e(g, SKH(M)) = e(SKg, H(M)) = e(PK, H(M))$. If so, the signature is verified.

In addition to public-key encryption, bilinear paring is useful for functional encryption, which is a generalization of public-key encryption in which possessing a secret key allows one to learn a function of what the ciphertext is encrypting. It provides a mechanism for accessing the function of the data without revealing actual data values. For example, if *Alice* wants to prove to *Bob* that she knew the answer of $x + y$ without revealing the value of x and y, she can send xg_2 and yg_2 to Bob, who then calculates $A = e(g_1, xg_2)e(g_1, yg_2)$, where g_1 and g_2 are generator points of elliptic curve groups G_1 and G_2. Since *Bob* knows the value of $x + y$, he can check whether $e(g_1, g_2)^{x+y}$ is equal to A to prove that *Alex* indeed knows the value of x and y [SHINDE, BSW2011, BSW2012, BUCH].

Note that general ECC and bilinear pairing use <u>different curves,</u> based on <u>different security assumptions,</u> and have <u>different trust models as listed in Table 1.</u>

Table 1. Elliptic curve used for general ECC and bilinear pairing.

	General ECC	**Pairing (IBE or ABE)**
Elliptic curve	Often use pre-defined Montgomery Curves or Edward curves. They do not have small embedding degree. ECC cannot use supersingular curves.	Curves with embedding degree *k*, *k* is small to make it pairing friendly. It can use supersingular curves.
Security assumptions	Discrete logarithm or Computational/Decisional Diffie-Hellman	Bilinear Diffie-Hellman (BDH) Problem
Trust models	PKI, use CA as a trusted party but CA does not access private key	Parameters need to be certified by a trusted 3rd party, e.g. PKI. The private key for each party is generated by a key generator which accesses everyone's private key.

3. Identity-Based Encryption

Identity-based encryption (IBE) is a functional encryption proposed by Adi Shamir in 1984 [ADI] that requires a trusted key generator to publish a master public key and retains the corresponding master private key (i.e., master key). The key generator allows any IBE user to generate a public key by combining the master public key with the user's identity value in text, such as an email address, name, or home address. The key generator also uses the master private key to generate the corresponding private key from the user's identity value. Thus, users may encrypt messages sent to other users without the prior distribution of a public key to other users. To decrypt or sign messages, the authorized user needs to obtain the appropriate private key from the key generator.

The Boneh-Franklin IBE encryption scheme [BF] applies the Weil pairing on elliptic curve over finite fields for setting up key management for public key and private key pairs from user identities for encrypting and decrypting messages, as constructed in the following.

The bilinear pairing function e: $G \times G \rightarrow G_T$, g is the generator of G, and p is the order of G and G_T. The parameters are:

Identity $I \in \{0, 1\}^*$ for message sender.

Message $M \in \{0, 1\}^m$

Hash function H: $\{0, 1\}^* \rightarrow G$

Extract function Q: $G_T \rightarrow \{0, 1\}^m$

Functions include:

Set up ( ) (by trusted key management server):

Return ($msk = Random\ (Z_p)$; $mpk = g^{msk}$). msk is the master secret key, which is for each public key of each access control system. *Random*( ) generates a random number.

Key generation(mpk, msk, I) (by trusted key management server for message receiver):

Return $sk = H(I)^{msk}$; sk is a private key for each identity.

Encryption(mpk, I, M) (for message sender):

$r = Random(Z_p)$; $R = g^r$; $K = e(mpk, H(I)^r)$; $W = Q(K) \oplus M$; $Return(R, W)$

Decryption(mpk, sk, R, W) (for message receiver):

$L = e(R, sk)$; Return $M = Q(L) \oplus W$; because $M = Q(L) \oplus Q(K) \oplus M$, and $L = K$ from the following:

$L = e(R, sk) = e(g^r, H(I)^{msk}) = e(g^{msk}, H(I)^r) = e(mpk, H(I)^r) = K$, where $H(\ )$ is a hash function. (Assume $H(I) = g^x$ for some x) [MIHIR].

Further, IBE offers the capability to encode additional information into identities. For example, a sender can specify the expiration date of a message by appending a timestamp to the recipient's identity (e.g., through some formal protocol like X.509). The receiver asks to retrieve the private key from the key manager (usually the key generator), who can evaluate the identity and decline the request if the expiration date has passed. Generally, embedding information in the identity provides an extra channel between the sender and the key manager with authenticity guaranteed in addition to the private key. The benefits of applying IBE can be demonstrated by an IBE email system:

- Senders can send mail to recipients who have not yet set up a public key.
- When sending email, there is no need for an online lookup to obtain the recipient's certificate.
- Senders can send email that can only be read at some specified time in the future.
- The system can proactively refresh the recipient's private key for a short time period [BONEH].

Note that the key generator can access the encrypted data for any receiver. And the communications between key generator and the receiver must be protected.

4. Attribute-Based Encryption

Attribute-based encryption (ABE) stems from IBE and is an encryption scheme that combines the principles of attribute-based access control [SP800-162] with the mechanisms of public-key cryptography. ABE allows data owners and data consumers to encrypt and decrypt data based on their attributes (e.g., organization, location, position), from which public and private keys are derived through third-party key manager. ABE eliminates the need for public-key distribution and certification , and the authenticity of the public keys is implicitly guaranteed as long as the transport of the private keys to the corresponding user is secure. ABE is especially useful for the system environment that requires pre-distribution of authenticated keys due to technical limitations.

ABE has the following basic properties:

- Encryption time and ciphertext size are linear to the number of attributes involved.
- Collusion resistance means that it is impossible to decrypt any ciphertext for any new attribute set (CP-ABE) or new access policy (KP-ABE) by giving any number of randomized private keys.
- Randomized encryption prevents users from distinguishing repeated encryptions of the same message for privacy [GOLIC].

Popular distributed systems, such as cloud and IoT, make it possible for users to access dynamic resources in flexible environments. However, their growth and the ubiquity of mobile devices for data access have generated new security and performance challenges. Many studies have been conducted on ABE, such as applying it to distributed systems [HL] for its one-to-many cryptographic scheme as well as the capability to store, transmit, and retrieve high-dimensional data with low computational time and high security. This shows that ABE can address security and privacy issues in outsourced and pervasive data access environments [ZDXSLZ]. For example, for the large attribute universe of a cloud system, ABE allows data owner to compose access control policies based on their applications so that they can provide delegation capabilities to data users [BS]. However, the implementation of ABE requires complex support infrastructures – including key generation services and data storing services – to manage access structures and coordinate between clusters of users.

ABE is classified into two main schemes: Ciphertext-policy ABE (CP-ABE) [BSW2007] and Key-policy ABE (KP-ABE) [GPSW]. Selective security[2] of CP-ABE is more suited to user attributes, while adaptive (full) security of KP-ABE is more suited to data (resource) attributes [GOLIC], as described in the following sections.

4.1. Ciphertext-Policy Attribute-Based Encryption

CP-ABE [BSW2007] enables data owners to define their own access policies over the user attributes and enforce those policies on data to be distributed. It provides a certain level of flexibility and scalability by removing the need for data owners to manage every individual access request and maintains an access control policy instead. Encryption and decryption of CP-

[2] For the challenger to private keys in the selective security model, the adversary has to commit the target attributes and declare the challengemessage (ciphertext) before public parameters are set up. The selective security model is weaker than the fully secure (adaptive) model, which has no restrictions as selective model, and both are given a public key, several secret keys, and one challenge ciphertext [WSOE].

ABE are based on the policy specified over the attributes so that a user can gain access to data if they have appropriate attributes. For example, the attribute set {*student*, *professor*, *TA*, *RA*, *registration*} contains attributes for student records. To encrypt *student records*, the school administrator specifies a policy rule: *professor* OR (*student* AND *TA*) OR *registration* for permitting access to *student records*. Thus, users who have attribute sets {*professor*} or {*student*, *TA*} can decrypt *student records*, but users who have attribute sets {*TA*} or {*student*, *RA*} cannot. CP-ABE is a useful scheme for addressing the risks associated with data security in a cloud system that needs key management and data storing services [MHH, BCSES] and to handle costumers with complex attribute structures.

Figure 4 shows the basic process steps of a CP-ABE scheme:

1. A trust authority generates public key *PK* and master key *MK* according to the applied attribute set and sends them to the key management service.
2. To access data, requester *x* sends their attribute set *Ax* to the key management service.
3. The key management service sends the public key *PK* to the data owner and generates secret key *SKx* for the data requester according to their attributes.
4. Using the public key, the data owner generates ciphertext *CT* for the data (*message*) based on the rules of their access control policy and then uploads the data to the data resource service.
5. The requester decrypts ciphertext *CT* from the resource service by using their secret key and attributes.

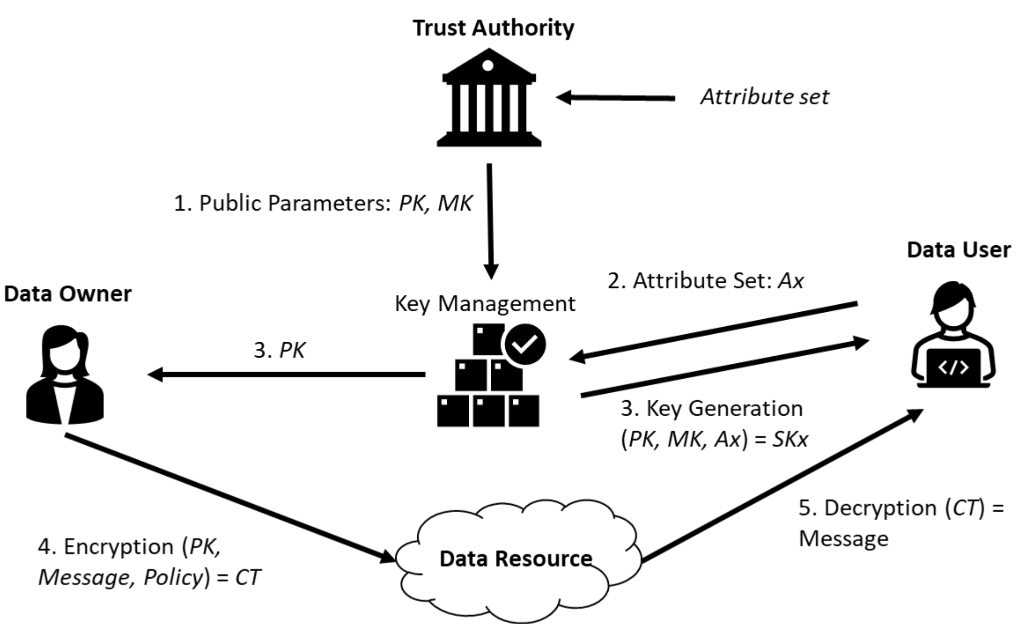

Fig. 3. Basic process steps of CP-ABE scheme

The master secret key *MK* can decrypt all ciphertexts, which CP-ABE uses to derive user secret keys associated with different attributes. Formally, global attribute set $A = \{a_1 \ldots a_n\}$, where a_1,

… a_n are attribute elements. User x has the attribute set A_x, which elements may or may not be in A. Let B be the Boolean rule structure (i.e., access control policy). For example, $B = a_1$ AND a_2 OR (a_3 AND a_4) for the data of a data owner. Note that the fundamental CP-ABE can only be applied to the Boolean logic of a policy rule with a non-monochrome (i.e., including "NOT" gate) structure. Key generation function *Keygen* (PK, MK, A_x) = SK_x, where PK is the public key, and MK is the master key. Decryption function *Decry* (CT, SK_x) = M, where CT is the ciphertext, SK_x is the secret (private) key for the user x, and the message M is rendered if the function $B(SK_x)$ checks the SK_x against the policy B is satisfied. Otherwise, M is NULL. Figure 5 shows an example structure of the access control rule and demonstrates the CP-ABE's algorithms for setup, encryption, key generation, and decryption functions.

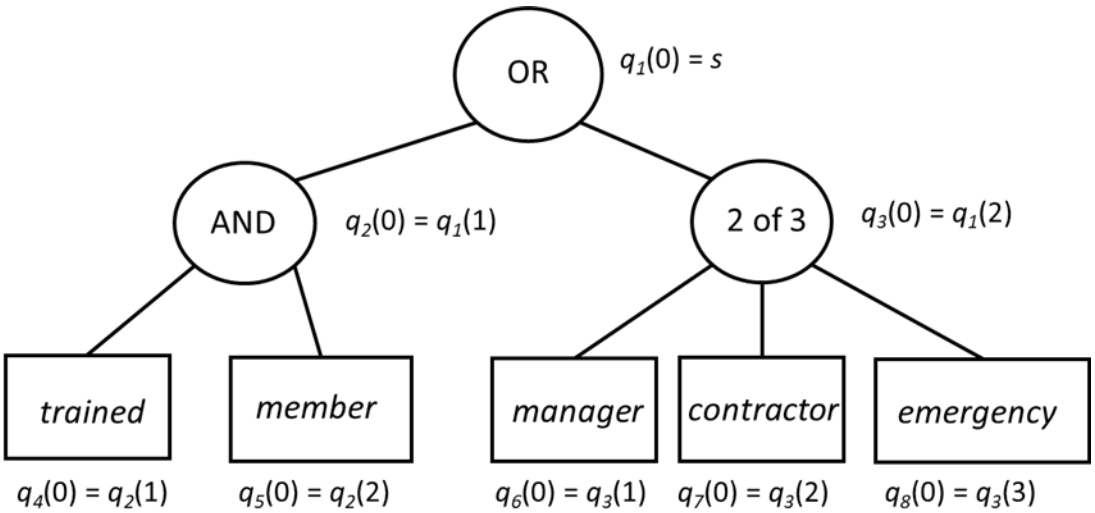

Fig. 4. The tree structure of an example access control policy

Setup function:

1. Master key MK = randomly chosen $\alpha, \beta \in Z_p$
2. Public key $PK = (G, g, g^{\beta}, e(g, g)^{\alpha}, g^{\frac{1}{\beta}})$, G is an elliptic curve group, g is the generator of the elliptic curve, $g^{\beta} = h$, and $g^{\frac{1}{\beta}} = f$ are for the delegation function (will not be discussed in this document).

Encryption function:

1. Let T be a tree representing an access structure as shown in Figure 5. Each non-leaf node of the tree represents a threshold gate, described by its children and a threshold value. If n is the number of children of a node x and k_x is its threshold value, then $0 < k_x \leq n$. The threshold value equals 1 for an OR gate (represented in a tree node of the Boolean operator on the node's children in the rule structure) and equals n for an AND gate with n elements or an n-out-of-m gate. Each leaf node x of the tree is described by an attribute and a threshold value $k_x = 1$.

2. Choose a polynomial q_i for each node q_1, q_2, …. q_8 for the tree structure that represents the access permission paths in the access control policy, as shown in Figure 5. Set Polynomial degree $d_i(q_i)$ = Threshold value $k_i(q_i) - 1$ for each node q_i.

3. Choose random s, such that root note $q_R(0) = s \in Z_p$, where p in Z is the order of the group G. For each node q_i, set $q_i(0) = q_j(n)$, where q_j is the parent node of q_i, and n is the sibling order from left to right. As shown in Figure 5, $q_1(0) = s$, $q_2(0) = q_1(1)$, $q_3(0) = q_1(2)$, $q_4(0) = q_2(1)$, $q_5(0) = q_2(2)$, $q_6(0) = q_3(1)$, $q_7(0) = q_3(2)$, $q_8(0) = q_3(3)$, , and according to 1, and 2 above, q_1 has degree 0, q_2 and q_3 has degree 1, q_4, q_5, q_6, q_7, and q_8 has degree 0.

4. Encryption $(M, T, PK) = CT = \{T, Me(g, g)^{\alpha s}, C = h^s$, and for each leaf q_x:

   $C_x = g^{q_x(0)}$, $C_x' = H(l)g^{q_x(0)}$, where x is the sibling order, and l is a string of one of a leaf in $T\}$. For example,

   $C_4 = g^{q_4(0)}$, $C_4' = H(\text{"}trained\text{"})g^{q_4(0)}$

   $C_5 = g^{q_5(0)}$, $C_5' = H(\text{"}member\text{"})g^{q_5(0)}$

   $C_6 = g^{q_6(0)}$, $C_6' = H(\text{"}manager\text{"})g^{q_6(0)}$

   $C_7 = g^{q_7(0)}$, $C_7' = H(\text{"}contractor\text{"})g^{q_7(0)}$

   $C_8 = g^{q_8(0)}$, $C_8' = H(\text{"}emergency\text{"})g^{q_8(0)}$

   Where M is the message (data), T is the access control policy tree of attributes, as shown in Figure 5. $e(,)$ is a bilinear mapping function, and $H( )$ is a hash function mapping to a point in G.

Key generation function:

Choose $\gamma \in Z_p$, and for each attribute of a user, for example, a user has attributes: A = {"*trained*", "*manager*", "*contractor*"}, choose $\gamma_{trained}$, $\gamma_{manager}$, $\gamma_{contractor} \in Z_p$.

Key generations $(A , MK) = SK = \{D = g^{\frac{(\alpha+\gamma)}{\beta}}$, $D_l = g^{\gamma}H(l)^{\gamma_l}$, $D'_l = g^{\gamma_l}$ } for all attributes the user has. For example,

$D_{trained} = g^{\gamma}H(\text{"}trained\text{"})^{\gamma_{trained}}$, $D'_{trained} = g^{\gamma_{trained}}$,

$D_{manager} = g^{\gamma}H(\text{"}manager\text{"})^{\gamma_{manager}}$, $D'_{manager} = g^{\gamma_{manager}}$,

$D_{contractor} = g^{\gamma}H(\text{"}contractor\text{"})^{\gamma_{contractor}}$, $D'_{contractor} = g^{\gamma_{contractor}}$,

where l is the string of one of a leaf in T.

(Note: MK contains α, β)

Decryption function:

Recursively go through the tree T to call *DecryptNode* (CT, SK, x). If the node x is a leaf node then we let $i = att(x)$ is a string of one of a leaf in T and define as follows: If $i \in S$ the set of all attributes in the tree, then

DecryptNode (CT, SK, x) =

$\frac{e(D_i,\ C_x)}{e(D'_i,\ C'_x)} = \frac{e(g^{\gamma}H(i)^{\gamma_i}, g^{q_x(0)})}{e(g^{\gamma_i}, H(i)^{q_x(0)})} = \frac{e(g^{q_x(0)}, g^{\gamma})e(H(i)^{\gamma_i}, g^{q_x(0)})}{e(g^{q_x(0)}, H(i)^{\gamma_i})} = e(g,g)^{\gamma q_x(0)}$ [MUKH].

Note that all leaves are attributes.

For example,

$\frac{e(D_{manager}, C_6)}{e(D'_{manager}, C'_6)} = e(g, g)^{\gamma q6(0)}$ (Note that $e(g,g)^{\gamma q_1(0)} = e(g,g)^{\gamma s}$)

For any leaf, return ⊥ (false) if it is not an user attribute.

If a node x is a non-leaf node, the algorithm proceeds such that for all nodes z that are children of x, it calls *DecryptNode*(*CT*, *SK*, z) and stores the output as F_z as following: Let S_x be an arbitrary k_x-sized set of child nodes z such that $F_z \neq \perp$. If no such set exists, then the node was not satisfied and returns ⊥. Otherwise, compute:

$F_x = \prod_{z \in S_x} F_z^{\Delta_{i,S'_x}(0)}$, where i = index(z) is the order number of the child. That is, S'_x = $\{index\ (z), z \in S_x\}$.

$= \prod_{z \in S_x} (e\ (g,g)^{\gamma q_z(0)})^{\Delta_{i,S'_x}(0)}$

$= \prod_{z \in S_x} e(g,g)^{\gamma q_x(i) \Delta_{i,S'_x}(0)}$ (i.e., $\prod_{z \in S_x} (e\ (g,g)^{\gamma q_x(index(z))})^{\Delta_{i,S'_x}(0)}$ by construction)

$= e(g,g)^{\gamma q_x(0)}$ (using polynomial interpolation)

For example: i = index(z) ∈ {1, 2, 3}, z ∈ {"*manager*", "*contractor*", "*emergency*"}

$F_{2of3} = F_{manager}^{\Delta_{1,(1,2,3)}(0)}\ F_{contractor}^{\Delta_{2,(1,2,3)}(0)} F_{emergency}^{\Delta_{3,(1,2,3)}(0)}$

$= (e(g,g)^{\gamma \cdot q_6(0)})^{\Delta_{1,(1,2,3)}(0)}\ (e(g,g)^{\gamma \cdot q_7(0)})^{\Delta_{2,(1,2,3)}(0)}\ (e(g,g)^{\gamma \cdot q_8(0)})^{\Delta_{3,(1,2,3)}(0)}$

$= e(g,g)^{\gamma(q_6(0)\Delta_{1,(1,2,3)}(0) + q_7(0)\Delta_{2,(1,2,3)}(0) + q_8(0)\Delta_{3,(1,2,3)}(0)}$

$= e(g,g)^{\gamma \cdot q_3(0)}$

Note that Lagrange coefficient: $\Delta_{i,s}(x) = \prod_{j \in s, j \neq i} \frac{x-j}{i-j}$, $i \in Z_p$ and a set, S, of elements in Z_p. For example:

$\Delta_{1,(1,2,3)}(0) = \frac{0-2}{1-2}\frac{0-3}{1-3} = 3$, $\Delta_{2,(1,2,3)}(0) = \frac{0-1}{2-1}\frac{0-3}{2-3} = -3$, and $\Delta_{3,(1,2,3)}(0) = \frac{0-1}{3-1}\frac{0-2}{3-2} = 1$. So,

$q_6(0)\Delta_{1,(1,2,3)}(0) + q_7(0)\Delta_{2,(1,2,3)}(0) + q_8(0)\Delta_{3,(1,2,3)}(0)$

$= 3q_6(0) - 3q_7(0) + q_8(0) = q_3(0)$ (i.e., $q_3(0) = 3q_3(1) - 3q_3(2) + q_3(3)$.

Since the algorithm started by simply calling the *DecryptNode* function on the root node R of the tree T, if the tree is satisfied by S, then *DecriptNote* (*CT*, *SK*, R) = $e(g,g)^{\gamma \cdot q_R(0)} = e(g,g)^{\gamma s}$. Then calculate the following to retrieve the message M (note that $q_1 = q_R$, $g^{\beta s} = h^s = C$) [KB, BSW2007]:

$\frac{Me(g,\ g)^{\alpha s}}{\frac{e(g^{\beta s}, g^{\frac{\alpha+\gamma}{\beta}})}{e(g,\ g)^{\gamma s}}} = \frac{Me(g,\ g)^{\alpha s}}{e(g,\ g)^{(\alpha+\gamma)s - \gamma s}} = \mathrm{M}$

An increasing number of organizations and individual users store their private data in open resources, such as cloud storage, for sharing with others. Unlike traditional access control, the data owners prefer to define their own access control policy rather than be controlled by a centralized access control policy. Thus, the data owners encrypt their data on the open resource according to their defined access control policy so as not to compromise it. CP-ABE provides appropriate solutions to meet data owners' needs because it enables data owners to define access control policies and hide them by masking off attributes [HR].

4.2. Key-Policy Attribute-Based Encryption

Another variation of ABE scheme is the KP-ABE [GPSW], wherein access control policies are associated with keys, and data is associated with attributes such that secret keys (private keys) are generated based on an access requester's attributes in the form of an access control policy. The ciphertext is labeled with a set of attributes so that decryption with a secret key works if and only if an attribute set built in ciphertext satisfies the structure of the access policy of the requester. Note that attribute sets can vary with each encryption.

Some access control models, such as multi-level and separation of duty security, are difficult to represent with straightforward Boolean formulas. In such cases, defining KP-ABE schemes to work with general Boolean circuits of attributes can be applied [TDN]. For example, to encrypt a secret document with attributes "*project_A*," "*project_B*," and " *project_C*," such that members involved in *project A*, *project B* OR *project C*, and *project A* OR *project D* can decrypt the document, but members involved in *project_A* AND *project_D*, and *project_A* AND NOT *project_C* cannot decrypt it.

Figure 6 shows the basic process steps of KP-ABE functions:

1. The trust authority generates public parameters – the public key *PK* and master key *MK* – according to the applied attribute set and sends them to the key management service.
2. To access data, the requester *x* sends their attributes and access structure (policy) to the key management service.
3. The key management service generates secret key *SKx* using *PK* and *MK* for the requester according to their attributes and associated access structure and sends the public key *PK* to the data owner.
4. Data owners generate ciphertext for the data (message) based on the applied attribute set and public key *PK* and then upload the data to the data resource provider.
5. The requester retrieves and decrypts ciphertext from the data source provider using their secret key *SKx* and attributes associated with access structure.

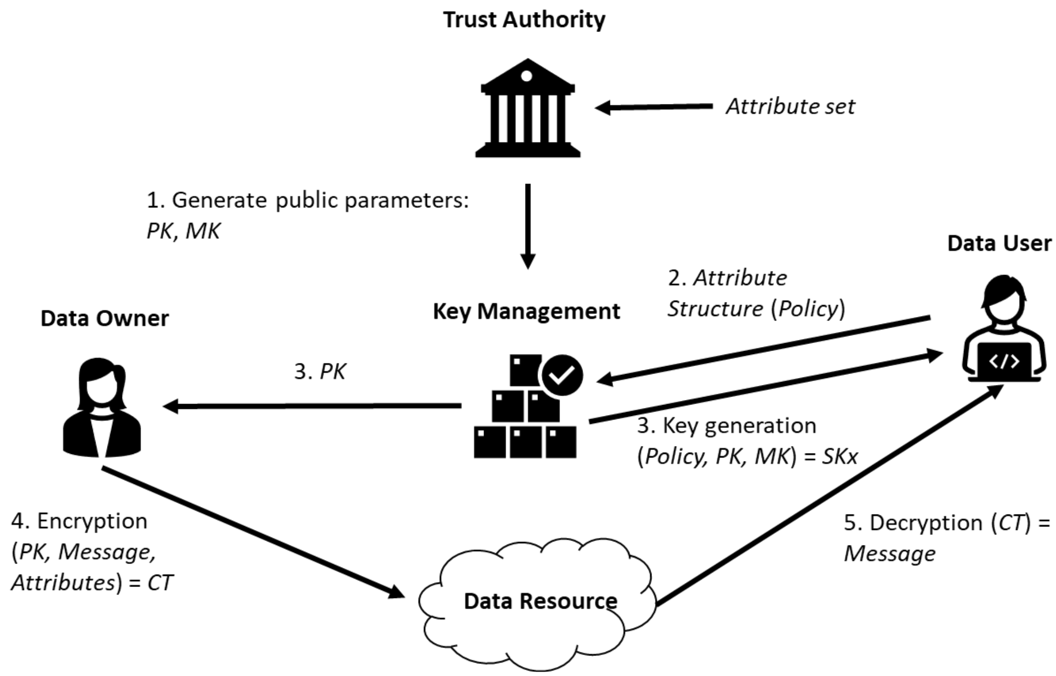

Fig. 5. Basic process steps of KP-ABE scheme

In general, the size of the public key of KP-ABE is linear to the total number of applied attribute sets. That is, the public key size is linear to the maximum number of attributes effectively used in encryption. However, it can be a fixed size in a random oracle large universe construction with hash function [GOLIC]. Using the example in Figure 5, instead of a policy structure of data, it now represents an attribute structure of a data requester. The following demonstrates an example of KP-ABE's algorithms of setup, encryption, key generation, and decryption functions.

Setup function:

- Bilinear map function e: $G_1 \times G_1 \rightarrow G_2$, G_1 has prime order p, and g is a generator of G_1.
- $U = \{ a_1, a_2, \ldots , a_n\}$ is a set of applicable n attributes. For this example, a_1 = "*trained*," a_2 = "*member*," … from Figure 5.
- t: $U \rightarrow Z_p$. Randomly choose $t_1, t_2, \ldots t_n \in Z_p$ from G_1, t_x for attribute x in U.
- Master key MK: Random $y \in Z_p$, $t_1, t_2, \ldots t_n$. and $Y = e(g, g)^y$
- Public key PK: Y, $T_1 = g^{t_1}$, $T_2 = g^{t_2}$, …., $T_n = g^{t_n}$

Encryption function:

$Encrypt(M, \gamma, PK) = C = (\gamma, MY^s, T_i^s \;\; \forall i \in \gamma)$, where random $s \in Z_p$, message $M \in G_2$, $\gamma \subseteq U$.
For example, γ = {"*trained*", "*manager*", "*contractor*"} for a user.

Key generation function:

The algorithm is the same as CP- ABE, but it is applied to each data requester instead.

$att(x)$: if x is a leaf node, then return the attribute associated with x

num(x): the number of children of a node x

$K(x)$: threshold value, $0 <= K(x) <= num(x)$

$K(x) = 1$, for an OR gate

$K(x) = num(x)$, for an AND gate with n elements or an n-out-of-m gate.
index(x): return node's index

- Choose a polynomial q_x for each node: $q_1, q_2, q_3, \ldots\ldots\ldots q_8$
- *degree* $(q_x) = K(x) -1$, *degree* $(q_1) = 0$, *degree* $(q_2) = 1$, *degree* $(q_3) = 1$, *degree* $(q_4) = 0$ ….. *degree* $(q_8) = 0$ as Figure 5 example.
- Access Tree: set root note $q_1(0) = y$, and chooses *degree* (q_1) other points of the polynomial q_1 randomly to define it completely. For example, in Figure 5: $q_1(0) = y \in Z_p$, $q_2(0) = q_1(1)$, $q_3(0) = q_1(2)$, $q_4(0) = q_2(1)$, $q_5(0) = q_2(2)$, $q_6(0) = q_3(1)$, $q_7(0) = q_3(2)$, $q_8(0) = q_3(3)$.
- For each leaf node x, $i = att(x)$ generates:

  $D = \{D_x = g^{\frac{q_x(0)}{t_i}}$ for all attributes a user has$\}$, for example,

  $D = \{ D_4 = g^{\frac{q_4(0)}{t_{trained}}}, D_5 = g^{\frac{q_5(0)}{t_{member}}}, D_6 = g^{\frac{q_6(0)}{t_{manager}}} \}$

Decryption function:

Inputs:

$C = (\gamma, MY^s, T_i^s\ \ \forall i \in \gamma)$

Private Key : D

Access Tree: T

With inputs, define a recursive algorithm *DecryptNode* (C, D, x) that takes a node x in the tree and outputs a group element of G_2 or $\perp$:

let $i = att(x)$. If the node x is a leaf node,

DecryptNode $(C, D, x) = e(D_x, T_i^s) = e(g^{\frac{q_x(0)}{t_i}}, g^{s \cdot t_i}) = e(g,g)^{s \cdot q_x(0)}$, if $i \in \gamma$, for example:

$e(D_6, T_{manager}{}^s) = e(g^{\frac{q_6(0)}{t_{manager}}}, g^{s \cdot t_{manager}}) = e(g,g)^{s \cdot q_6(0)}$

$e(D_7, T_{contractor}{}^s) = e(g^{\frac{q_7(0)}{t_{contractor}}}, g^{s \cdot t_{contractor}}) = e(g,g)^{s \cdot q_7(0)}$

If x is not an attribute in leaf, then return $\perp$. If x is a non-leaf node, then proceeds as follows: for all nodes z that are children of x, call *DecryptNode*(C, D, z), and store the output as F_z. Let S_x be an arbitrary k_x-sized set of child nodes z such that $F_z \neq \perp$. If no such set exists, then the node was not satisfied, and the function returns $\perp$. Otherwise, compute:

$F_x = \prod_{z \in S_x} F_z^{\Delta_{i,S'_x}(0)}$, where $i = index(z)$, is the index number of child node z, S'_x = (*index*(z), Z

$\in S_x$), and Lagrange coefficient: $\Delta_{i,s}(x) = \prod_{j \in s, j \neq i} \frac{x-j}{i-j}$, $i \in Z_p$ and a set, *S,* of elements in Z_p.

$= \prod_{z \in S_x} (e(g,g)^{sq_z(0)})^{\Delta_{i,S'_x}(0)}$

$= \prod_{z \in S_x} (e(g,g)^{sq_{parent}(index(z))})^{\Delta_{i,S'_x}(0)}$ (by construction)

$= \prod_{z \in S_x} e(g,g)^{sq_x(i)\Delta_{i,S'_x}(0)}$

$= e(g,g)^{sq_x(0)}$ (using polynomial interpolation). For example:

$(e(g,g)^{sq_6(0)})^{\Delta_{1,(1,2,3)}(0)}\ (e(g,g)^{sq_7(0)})^{\Delta_{2,(1,2,3)}(0)}\ \ e(g,g)^{sq_3(0)} = \mathrm{e}(g,g)^{sq_1(0)} = e(g,g)^{sy}$.

Hence, $q_6(0) = q_3(6)$, $q_7(0) = q_3(7)$, $q_3(0) = q_1(3)$.

If and only if the ciphertext satisfies the tree, then $DecryptNode(C, D, x) = e(g, g)^{sy}$. Since $MY^s = Me(g, g)^{ys}$, simply divide out $e(g, g)^{ys}$ to recover the message *M* [HALL, GPSW].

KP-ABE is also useful for searching encryption contents from categorized attributes. For example, searching video from attribute set = {*a*, *b*, *c*, *d*, *e*} (*a* is title, *b* is actors, *d* is directors, *e* ……), users can decrypt with search criteria – such as *a*, *b* OR *c*, *d* AND *e*, and *a* OR *e* – because they are all in the attribute set, but users cannot decrypt with search criteria *a* AND *f*, *d* AND (NOT *e*), *b* AND (NOT *c*), *f* because the attribute set cannot satisfy the search criteria defined by attribute set [GOLIC].

5. ABE System Considerations

The ABE encryption scheme allows for higher data scalability, less computational time, low memory usage, and large-scale deployments of system platforms [KKB] in comparison to traditional PKE. However, for applications, it suffers from the drawbacks of low efficiency, less expressive access policies, and the use of random oracle models. Thus, the deployment and adoption of ABE have been slow. According to [ELT], ABE is absent from common data products and formats that are generated by widely used commercial authoring products (e.g., Microsoft Word documents, Excel spreadsheets, PowerPoint slides) for lacking selective and fine-grained control over what is shared and with whom. In general, even with specific modifications or add-on applications (e.g., blockchain), implementation of ABE applications should consider security, performance, and access control policies/model supports.

5.1. Security

ABE provides confidentiality and data integrity when used in a public environment with a large scope (e.g., cloud) of users. However, relying only on user-specified attributes may create various security issues from the perspectives of key management processes and intentional threats or attacks.

5.1.1. Key Management

Secure communication: To distribute keys to users, a secure communication channel between a user and the key management service is required such that an SSL-like connection is a common solution for a large-scale ABE system. Hence, it is important for users to authenticate themselves through – for example – usernames, passwords, or public key pairs managed on user devices.

Non-repudiation: Because the key management service generates private keys for users, it may decrypt without authorization. If the secret key is abused, it is difficult to judge whether the abused private key comes from users or the key management service [WZZGZZ]. Therefore, ABE systems are difficult for non-repudiation. This may not be an issue for organizations that host their own key management service and are willing to trust their system administrators or that do not require non-repudiation. A caveat is that the key management service must be highly trusted.

User tracking: The problem of the basic ABE scheme is that there is no mechanism to identify the user who is issued a key. The secret key does not contain the specific information of users, so it is impossible to identify the user who misuses the distributed key or shares their secret key with other users [WZZGZZ]. A tracking function might be required for higher security requirements. However, providing traceability may infringe on a user's privacy by exposing the user's identifier value when the key is issued by the attribute verification [HL] process of the key management service.

Key escrow: Because a user's private key is generated through the key management service, ABE has the capability of key escrow. However, such a capability can be a positive or negative feature depending on the usages, such as a private organization using it for security control while sacrificing the privacy of its users. Several variant ABE systems have been proposed that remove the escrow by replacing encryption or key generation processes with certificate-based encryption [CRAI], secure key issuing cryptography [BCEKJS], or certificateless cryptography [AP].

Key revocation: One of the major advantages of any identity encryption scheme is that a third party's secret key can be destroyed after all users have been issued keys and if there is only a finite number of users. This can take place for ABE system as well because it assumes that keys are always valid once issued, and there is no method for key revocation to handle secret keys due to expiry of embedded attributes, faulty access policies, or key compromise. Key revocation for ABE can be handled by including the expiry time/date among the attributes, periodic refreshing, and revocation lists [GOLIC].

5.1.2. Threats and Attacks

Compromised key management server: ABE relies on a key management service for the generation of cryptography keys. If the key management service is compromised, data protected by the public-private key pair used is also compromised. Hence, a key management service is a high-value target for adversaries who wish to decrypt all ciphertexts. A countermeasure for this vulnerability is to frequently update the master private-public key pairs with new independent key pairs for all users. However, this complicates the key management process.

Collusion: CP-ABE users can infer other users' attributes through collusion with each other, generate another user's secret key with the inferred attributes, and share private decryption keys (and maybe attribute certificates if applicable) [MIHIR]. Therefore, when a key management service generates a secret key, it must do so by applying various variables in addition to the user's attributes. If data leaks through a collusion attack on resource providers, security technology is required so that only a legitimate user can decrypt and view the ciphertext [MIHIR].

Fully secure: Fully secure (i.e., adaptive) ABE is more advantageous than selectively secure ABE because it does not require adversaries to specify their target access policies or attribute lists until they receive the system public keys. General ABE schemes based on prime order groups for cryptography lack the proof of fully secure, so efforts in proof methods are needed to promote more secure and efficient designs. Existing fully secure ABE solutions are usually designed on composite-order groups or re-encryption[3] systems, and complex assumptions are involved in the security proof [ZDXSLZ, HL].

Integrity: Outsourcing servers for an ABE system requires trust so that the decrypted ciphertext is a legitimate message based on legitimate user attributes. Additionally, the message uploaded to the resource provider can be falsified, and it is unknown whether the value calculated by the outsourcing server is the correct value. Accordingly, it is necessary to verify whether the user's final decrypted value is the original message from the data owner [HL]. Specifically, verification processes are required to prove that the results computed from key management and resource servers are properly computed.

[3] Proxy re-encryption (PRE) allows a proxy to convert a ciphertext encrypted under one key into an encryption of the same message under another key. The main idea is to place as little trust and reveal as little information to the proxy as necessary to allow it to perform its translations [uma].

Quantum resistant: ABE systems are insecure against quantum computer attacks. Many public-key encryption schemes – including ABE – require security enhancements to resist possible quantum attacks. Although lattice-based algorithms can resist quantum attacks, there are only a few lattice-based ABE constructions that are selectively secure. In addition, lattice-based schemes lack practicability because they have only been considered secure for inefficiently large parameters. Thus, more attention should be paid to anti-quantum ABE for better security assurance [ZDXSLZ, DKW, WWW].

5.2. Performance

A performance bottleneck of ABE is the high computation overhead due to the complexity of the embedded bilinear pairing algorithm and the requirement for large security parameters [OD] to cover a wider scope of attributes.

5.2.1. Computational Complexity

Most of the existing ABE schemes, (e.g., such as revocable ABE, accountable ABE, policy-hiding ABE, ABE with policy updating, and multi-authority ABE) have a high order of computational complexity for typical cryptographic operations – including exponentiation, point multiplication, group arithmetic operations, and especially, the bilinear pairing calculation – that are much greater than that of symmetric and traditional PKE [ZDXSLZ]. Therefore, it may be more efficient to apply alternative schemes like non-bilinear pairing-based ABE schemes [KAB] for practical uses of ABE, especially in a resource-constrained system environment such as IoT.

5.2.2. Keys and Ciphertext Size

Both CP-ABE and KP-ABE schemes have overhead issues with key size. In CP-ABE, the public key size can be fixed with a hash function or made linear to the number of attributes applied. In KP-ABE, the size of the public key is linear to the maximum number of attributes applied to the system [GOLIC]. The size of the ciphertext depends on the number of available attributes contained in the access structure, and it increases linearly with the number of attributes, which requires significant system storage and computation time for users to decrypt ciphertext. Therefore, it might be necessary to introduce assistant systems to accommodate the heavier computation (e.g., increase the computational efficiency with architecture options, such as proxy devices [MHR]), but a verification process is needed to prove that the results on the outsourcing server are properly computed [HL]. Further, CP-ABE is not efficient for modern enterprise environments when compared to KP-ABE due to that the resource access policies needed for central management such that when a policy changes, secret keys need to be re-established for users. In contrast, KP-ABE is made more flexible by its broadcast type of encryption [UMAS] for user policies.

5.2.3. Physical Limitations

The physical properties of ultra-low energy mobile devices [OD] include low processing power, a distributed nature, and a lack of standardization [RPRMK], which limit their capabilities for performing complex computations to support ABE's (especially CP-ABE's) encryption and decryption. These drawbacks hinder ABE adoption for advanced applications, such as IoT and cloud systems, due to the much greater heterogeneity and resource restrictions of their devices. Therefore, further investigation into the application of ABE is needed to decide device sizing against levels of computation, communication, and performance. Mobile computing for ABE has established its own paradigm, which has extended to researching whether ABE for mobile devices can be translated to the application of IoT [MHR].

Researchers are currently working on blockchain fundamentals and customizing blockchain-based ABE models for IoT applications to provide privacy and minimize computational overhead. For example, [QYLPYH] use a lightweight blockchain ABE to outsource decryption based on the blockchain, which can be extended to effectively reduce the burden of encryption computation on the user side. Blockchain technology can also provide integrity (i.e., the secret key does not contain the specific information of users who may share their secret keys with other users) and the non-repudiation of data, as well as prevent the leaking of sensitive information from ABE access structure [WZZGZZ].

5.3. Access Control Policies and Model Supports

In addition to functionalities like revocation, accountability, attribute privacy protection, policy updating, decentralization (multi-authorities), and key hierarchy for practical access control system deployments [ZDXSLZ], the applicable access policy structure for ABE is restricted to supporting non-monotone and stated policy rules [TKN]. For example, CP-ABE allows data owners to define their own access policies (structures) by attributes and, thus, support complex access control policy structure. However, by only associating attributes, decryption keys are organized logically as a static set. Users can only use all possible combinations of attributes in the set of keys issued to compose their policies, and it has restrictions for specifying policies, attribute managements (e.g., applying environment conditions and dynamic attributes), and the application of deny rules, which fails to satisfy the enterprise requirements of access control in terms of flexibility and dynamic requirements [BS].

In KP-ABE, the secret key and ciphertext relate to a set of attributes to offer fine-grained access control [BCSES] for which permission evaluation depends only on the resources' attributes. The resource provider (i.e., data owner or encrypted) cannot specify the access policy except by choosing descriptive attributes for permissions. This means there is no choice but to trust the key issuer. Such accountability for user secret keys provides fine-grained access without flexibility or scalability [BS], making it unsuitable for certain applications unless supported by re-encryption techniques [GOLIC].

Further, from the perspective of full access, action capabilities – including write, modification, and execute privileges – are not straightforwardly implemented in ABE schemes and thus require other layers of operational support.

6. Conclusion

ABE supports fine-grained access control for encrypted data and is a cryptographic scheme that go beyond the all-or-nothing approach of public-key encryption schemes. This document reviewed the interplay between cryptography and the access control of ABE, from fundamental theories on which the ABE scheme is based to various main algorithms of IBE, CP-ABE, and KP-ABE, as well as considerations for deploying ABE systems.

Due to security, performance, and access control policy/model support considerations, the deployment and adoption of ABE have been slow. Few commercial widely used products (e.g., Microsoft Word, Excel, PowerPoint) use it to date. This shortcoming of selective and flexible access control might impact its adoption for government and commercial applications as well as applications for highly secure demanding areas (e.g., life sciences, healthcare, financial sectors) [ELT]. However, with additional exploration and the support of additional outsources or processing systems, a mature ABE technology can address these challenges.

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