Attribute-based Encryption for Attribute-based Authentication, Authorization, Storage, and Transmission in Distributed Storage Systems

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1 Overview

Attribute-based encryption is a form of encryption which offers the capacity to encrypt data such that it is only accessible to individuals holding a satisfactory configuration of attributes. As cloud and distributed computing become more pervasive in both private and public spheres, attribute-based encryption holds potential to address the issue of achieving secure authentication, authorization, and transmission in these environments where performance must scale with security while also supporting fine-grained access control among a massively large number of consumers. With this work, we offer an example generic configurable stateless protocol for secure attribute-based authentication, authorization, storage, and transmission in distributed storage systems based upon ciphertext-policy attribute-based encryption (CP-ABE), discuss the experience of implementing a distributed storage system around this protocol, and present future avenues of work enabled by such a protocol. The key contribution of this work is an illustration of a means by which any CP-ABE system may be utilized in a black-box manner for attribute-based authentication and cryptographically enforced attribute-based access control in distributed storage systems.

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2 Background

In this section, we (1) provide an introduction to attribute-based encryption, (2) briefly introduce the premise and significance of distributed storage, and (3) motivate a need for a secure attribute-based authentication, authorization, storage, and transmission protocol by identifying security concerns in the distributed systems underlying cloud environments.

2.1 Attribute-based Encryption

Attribute-based encryption (ABE) is a form of encryption first proposed by Sahai and Waters as an application of fuzzy identity-based encryption, a type of encryption through which data is encrypted on the basis of individual identity as represented by a set of attributes [9]. Goyal et. al. later explored the topic in more detail, presenting attribute-based encryption as a generalization of this construction in which data is encrypted according to some logical expression of attributes, called an access policy, such that encrypted data can only be decrypted if that policy is satisfied [5]. The authors of [5] further defined a formal security setting for an ABE scheme: in addition to the cryptographic guarantees (e.g. IND-CPA security) expected of encryption schemes in general, a useful ABE scheme must also be resistant to collusion attacks, defined as an attack in which one or more key holders attempt to decrypt data for which they are otherwise not authorized by sharing keys.

In its discussion of attribute-based encryption, the authors of [5] discuss two forms of attribute-based encryption: ciphertext-policy ABE (CP-ABE) and key-policy ABE (KP-ABE). The core difference between ciphertext-policy ABE and key-policy ABE lies in the logical location of the access policy: in CP-ABE, a set of attributes is associated with a key, and encrypted data can be decrypted only if those attributes satisfy the access policy associated with it; in KP-ABE, a set of attributes is associated with encrypted data, and data can be decrypted only if those attributes satisfy a policy associated with the key being used. To illustrate both the utility of ABE and the differences between CP-ABE and KP-ABE, consider the following two illustrative scenarios:

Scenario 1: Company C maintains a file F which contains confidential salary information for employees in New York. F should be encrypted and stored such that it can only be read by either the company CEO or managers in New York.
This end could be achieved using CP-ABE as follows: first, grant users keys containing attributes corresponding to their position and their office location; next, encrypt $F$ using the policy CEO or (Manager and New York). In the future, depending on the security of the chosen ABE scheme and its application context, only an individual whose key satisfies this policy may decrypt and read the contents of $F$.

**Scenario 2:** Agency $D$ maintains a file $F$ which contains a report on confidential material. Each section of the report contains content surrounding some subset of topics. An individual $A$ is authorized to read any classified material so long as it concerns both Europe and agriculture.

This end could be achieved using KP-ABE as follows: first, encrypt $F$ in segments, associating a set of attributes corresponding to the set of sensitive topics contained. Next, issue $A$ a key with the policy Europe and Agriculture. $A$ will then, depending on the relative security of the ABE scheme, be able to decrypt and read only those sections containing information on both Europe and agriculture.

As is iterated in [5], CP-ABE and KP-ABE are suited towards different use cases. Intuitively, between the two components required for decryption—ciphertext and key—the one with which the policy is associated imposes a more selective condition than the other. As we are concerned with use cases in which access to remote data by consumers is controlled by policy, this work makes exclusive use of CP-ABE.

### 2.2 Ciphertext-policy Attribute-based Encryption

A valid CP-ABE scheme must provide four algorithms: \textit{Setup}, \textit{Encrypt}, \textit{GenerateKey}, and \textit{Decrypt}, defined in greater detail below:

- **\textit{Setup}(\lambda, U):** Takes a security parameter $\lambda$ and a description of attributes within the system $U$ and outputs a set of public parameters $PK$ and a master key $MK$.

- **\textit{Encrypt}(PK, M, A):** Takes a set of public parameters $PK$, a message to encrypt $M$, and an access policy $A$ expressed in terms of attributes and outputs a ciphertext $C$, generally assumed to also contain $A$.

- **\textit{GenerateKey}(MK, S):** Takes a master key $MK$ and a set of attributes that should be associated with the key $S$ and outputs a private key $SK$.

- **\textit{Decrypt}(PK, C, SK):** Takes a set of public parameters $PK$, a ciphertext to decrypt $C$, and a secret key $SK$ and outputs the decrypted message $M$. 
In works such as [2], authors have since introduced extensions to CP-ABE which allow for the construction of multi-authority CP-ABE schemes. In multi-authority and hierarchical CP-ABE schemes, multiple authorities work with one another to generate keys (at times with each authority being responsible for some possibly disjoint subset of attributes).

Although these variants of ABE define slightly different interfaces for each algorithm, for the sake of this work, any reference to Setup or GenerateKey may be assumed to reference the interface provided by any one individual CP-ABE scheme (single-authority, multiple-authority, or otherwise) so long as said scheme (a) defines Encrypt and Decrypt as specified and (b) does not assume a static universe of attributes.

2.3 Cloud Computing and Distributed Storage

Cloud computing is a model which enables on-demand access to a shared pool of configurable computing resources; a primary objective of cloud computing is the capacity to rapidly provision and release these resources with minimal effort on the part of the service provider as required by the measured needs of consumers; this allows applications to arbitrarily scale to meet the needs of one consumer or billions of consumers [8]. NIST defines three service models of cloud computing: Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS): SaaS allows shared access to the providers application running on cloud infrastructure; PaaS provides shared access and management of languages, tools, and services required to deploy an application; IaaS provides shared access to fundamental hardware resources such as disk space, networks, and CPU cores [8].

Data-intensive applications that ultimately either rely on or support SaaS or PaaS service models inherently require logical data storage and access at scale. While all service models guarantee that storage space may be provisioned as necessary, support for shared distributed storage among these resources is required by applications which need to operate concurrently on contiguous data. To meet this need in a manner optimal for their respective use cases, various distributed storage systems have been developed. To provide a non-exhaustive set of examples: GFS is a distributed storage system developed by Google to provide general-case fault-tolerant, scalable storage over commodity hardware [4]; HDFS is a distributed storage system implemented to meet the storage needs of a specific cluster computing framework [10]; DynamoDB is a distributed storage system implemented by Amazon to support the access pattern defined by its shopping cart feature [3].

2.4 Security in Distributed Storage Systems

While the many distributed storage systems which exist are intentionally highly performant, available, and scalable, their initial design does not directly guarantee congruent security of stored data. In this section, we demonstrate the deficiencies that exist in such systems with respect to confidentiality and integrity of data stored, and we further illustrate the limits of common approaches to addressing these deficiencies.

Confidentiality. Consider the confidentiality of data stored by a distributed storage system. If, as described in [4], [10], and [3], stored resources are served to any requesting entity, the confidentiality of data intended to be accessible by a specific subset of users cannot be guaranteed. A distributed storage system expected to ensure confidentiality of data must implement some means of access control; to do so, such a system must also have a means of reliably discerning an authorized user from a non-authorized user (potentially via authentication) and subsequently enforcing access control. Confidentiality, however, is still not absolutely guaranteed by sound authentication, authorization, and access control: if data is stored in the clear, any unauthorized party gaining access to a storage node inevitably gains access to the data residing at that node. Similarly, if data or control messages are transmitted in the clear, an unauthorized party may gain knowledge of data directly or indirectly by simply eavesdropping.

Integrity. Consider the integrity of data stored by a distributed storage system. If both system components and consumers accept control messages and data transferred blindly, an attacker could potentially influence
either the server or the client to accept invalid data by modifying the stream of data sent. Similarly, if an attacker gains access to a storage node, integrity is trivially compromised by means of the fact that such an attacker may then arbitrarily modify data. This latter risk to integrity is somewhat offset by the structure of distributed storage systems making use of replication: in such systems, breaches to integrity may be corrected by means of copying from a replica.

Though offering secure access control, storage, and transmission may allow a distributed storage system to preserve the confidentiality and integrity of stored data, the question of how a distributed storage system might do so in a genuinely secure manner without affecting performance or scalability of the system remains a challenge. In practice, systems attempt to resolve these concerns by means of either symmetric-key encryption and/or public-key encryption; however, the constraints imposed by conventional symmetric and public-key cryptography degrade feasibility and security at scale in an environment in which resources are not restricted based upon the unique identity of the consumer.

As an example, HDFS, a popular distributed storage system used commonly in support of cluster computing, implements an approach which utilizes symmetric-key encryption: HDFS introduces the notion of an encryption zone, in which the aim is for files to be securely shared between consumers in a zone [1]. Each file in an encryption zone is encrypted using a symmetric cipher using a random key, which is itself stored encrypted under a zone encryption key, shared among all consumers in the zone [1]. This approach, however, merits caution with respect to both security and feasibility. With respect to security, this approach may not be optimal, as it requires keys to be shared between a large number of consumers for large zones; with respect to feasibility, this approach may not be optimal, as each consumer must store one key for each to which he or she has access.

Unlike symmetric-key and group-based approaches to addressing the above issues, an approach utilizing attribute-based encryption inherently comes with the capacity to express fine-grained access control without having to track the identity of users or perform burdensome key management at a scale linear in the number of groups of files to which a user has access. Furthermore, attribute-based cryptography admits a means for allowing consumers to authenticate and be authorized on a basis other than identity, a pattern more suited for distributed storage systems seeking security at scale.

2.5 Related Work

Attribute-based encryption has been identified previously as a potentially useful basis for security in distributed storage systems and cloud computing. Early works on attribute-based encryption such as [5] and [9] reference applications for which ABE may be promising, including broadcast log encryption, an application also essential for the auditing of the distributed systems underlying cloud environments.

Other works, such as [6], [7], and [12], point out potential gaps in ABE as given canonically, aiming specifically to provide some extension of ABE which might satisfy the requirements of a storage application in a cloud environment. [12] aims to introduce a provably secure hierarchical ABE (H-ABE) construction to allow for more flexibility in system architectures employing ABE; [7] aims to provide a multi-authority ABE construction to fulfill a similar need while also fulfilling anonymity requirements; [6] identifies a particular necessary capability of large-scale operating systems–key revocation–and provides a provably secure construction meant to reduce the computational burden of key revocation at the cost of a slight overhead in encryption and decryption. CP-ABE, Wang et. al. have proposed a system called Sieve which utilizes KP-ABE in untrusted cloud environments, with a particular focus on web services. [11].

This work is distinct from previous works in that, rather than providing a specific ABE construction or a system to be utilized by other systems and services, it provides (a) a generic configurable protocol which uses CP-ABE to achieve secure access, storage, and transmission of distributed resources in generic distributed storage systems and (b) a generic threat model that may be used to analyze any such protocol providing access control on the basis of attributes. As a result, a system utilizing this protocol may opt to choose one from among all ABE schemes according to its unique performance and security expectations; likewise, the threat model provided may be used as a basis of analysis for alternative systems and protocols. The protocol proposed further separates the function of recovery from the cryptographic scheme used,
providing a feasible means of directly performing key revocation and recovery without having to rely on ad-hoc qualities of the configured cryptosystem.

3 The Protocol

In this section, we (1) introduce a general, high-level architecture abstraction used to represent the system which will house our proposed protocol, (2) briefly introduce preliminaries of our proposed protocol, and finally (3) outline the protocol.

3.1 System Setting

The basic protocol introduced is defined with respect to a system which provides access to distributed resources to consumers (semi-anonymous or identified) who interact with the system on the basis of their attributes. Such a system is assumed to be composed of some number of system components called nodes, each of which taking one of the following roles with respect to the protocol:

- **Authorization Node**: Entity responsible for performing authorization of consumers on some subset of attributes recognized within the system.

- **Service Node**: Entity responsible for providing a secure interface to some subset of partitions of distributed resources. Consumers communicate with service nodes to access or modify distributed resources.

- **Authority**: Entity responsible for creating keys and arbitrating the global universe of attributes recognized by the system. An authority may delegate to other components to perform key distribution.\(^1\)

\(^1\)The protocol given admits potentially many key distribution schemes. See Future Work
Figure 1: Example configuration of roles among system components.

Figure 1 provides an illustration of such an architecture containing \(m\) authorization nodes and \(n\) disjoint service nodes. A consumer first authenticates to and is authorized by an authorization node for some subset of attributes, and he or she is then serviced by service node 1 on partition \(x\) and service node \(n\) on partition \(y\). This specific configuration of component roles reflects a system architecture using many \((m)\) masters and many \((n)\) storage nodes.

Though the example in Figure 1 is specific, the abstract system setting described may be configured to map to any general distributed storage system: this configuration may be modified, for example, to map to a single-master system by reducing the number of authorization nodes to one; alternatively, it could be modified to map to quorum-like system architectures by making the sets of authorization nodes and service nodes non-disjoint\(^2\). Note also that this setting allows a system to decouple the location of consumer authorization from the location of the master key holder (the authority) within the utilized ABE scheme; any such coordination of roles may be easily extended to employ multiple or hierarchical authorities if using a multiple-authority ABE scheme.

### 3.2 Preliminaries

The proposed protocol makes use of additional abstractions defined with respect to attributes.

**Definition 3.1. Representation** The representation of an attribute is the functional component of a named attribute within an ABE construction.\(^3\)

\(^2\)This latter case would require the coordination techniques applied in quorum-like systems to also be applied to authorization nodes. See Future Work

\(^3\)Example: in a hypothetical ABE scheme in which an attribute is manipulated or applied mathematically using a group element unique to that attribute, the representation of an attribute would be its respective group element.
Definition 3.2. *Volatile Attribute* A volatile attribute is an attribute whose representation may be expected to change.

Definition 3.3. *Manifest Attribute* A manifest attribute is an attribute whose representation must necessarily be known to parties outside of the set of system components.

Definition 3.4. *Bound Attribute* A bound attribute is an attribute whose representation is coupled with the state of some resource.

To illustrate the meanings and uses of these abstractions, consider the task of encrypting a large file using ABE. If the policy on the file involves the attribute $A$, $A$ becomes a bound attribute. If $F$ must be accessible to external consumers, $A$ also becomes a manifest attribute. We would hope that $A$ is not also a volatile attribute, as any change in its representation would cause the system to need to re-encrypt $F$; similarly, if a volatile attribute $A$ were to become manifest, it may become necessary to propagate the new representation of $A$ to interested consumers.

In addition to these abstractions of attributes, the protocol proposed defines additional constructs to be used in the authentication and authorization process.

Definition 3.5. *Master Session Token (MST)* An object produced as a result of authorization which authenticates consumer attributes to a service node and contains authorization from an authorization node.

Definition 3.6. *Validity Attribute* A validity attribute is a volatile, manifest attribute assigned to consumers whose primary role is to attest to the validity of the key of a requesting consumer. When a consumer authenticates to an authorization node, the consumer must specify a set of held validity attributes, and the produced MST is sent such that it may only be used if the consumer holds all of the attributes with which he or she authenticated as well as the validity attributes specified. A validity attribute will never be bound to a file resource served by the protocol.

### 3.3 Protocol Definition

The proposed protocol is composed of seven configured algorithmic components:

1. An attribute-based encryption scheme $E_{ABE}$
2. An attribute-based encryption scheme under a variable-length mode of encryption $E_{CHAIN}^4$
3. (Optional) An attribute-based signature scheme $S_{SIG}$
4. A public-key signature scheme $S_{PSIG}$
5. A variable-length symmetric-key encryption scheme $E_{SYM}$
6. A MAC scheme $MAC$
7. A secure key exchange routine $R_{KE}$

The only constraint placed on these components is that $E_{ABE}$ must be able to encrypt ciphertexts at least as large as the size of keys and parameters for $E_{SYM}$. If there is no single entity that is to be absolutely identifiable among system components, $S_{SIG}$ should be configured as an attribute-based signature scheme. If $S_{SIG}$ is not configured, public-key $S_{PSIG}$ is used in its place.

In addition to the configured algorithms, the following parameters must also be configured:

1. Role assignment for system components (mapping system components among authorities, service nodes, and authorization nodes)

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4This may be derived from $E_{ABE}$. See Implementation and Future Work.
2. Parameters $x$ and $u$, respectively configuring the number of validity attributes to be used by the system and the minimum number of validity attributes a consumer must advertise in order to authenticate.

System initialization. At system initialization, the configured authority (or authorities) perform the \textit{Setup} algorithm as specified by $E_{ABE}$, with an initial universe $U$ containing an attribute $SN$ to be issued for provisioned service nodes, an attribute $a_i$ for each initial generic manifest attribute to associate with consumers and to be bound to stored resources, an attribute $AN_{A_j}$ for each subset of attributes $A_j$ to be authorized exclusively by some subset of authorization nodes, and all validity attributes $v_1...v_x$.

Addition of new components. When a new authorization node is provisioned, that node is issued a $ABE$ key containing the attribute $AN_{A_j}$ corresponding to the subset of attributes $A_j$ for which it is responsible for authorizing and a public key pair if $S_{SIG}$ has not been configured. When a new service node is provisioned, that node is issued an $ABE$ key containing the attribute $AN_{A_j}$ and all validity attributes.

Note: This protocol allows component locations and responsibilities to be public knowledge. For the sake of simplicity and generality, this work assumes that there is a public index of all public parameters (including a whitelist of locations, responsibilities, and public parameters of $E_{ABE}$) that reflects changes immediately; private changes (including the issuance of keys) are assumed to be communicated by means of a generic secure key distribution mechanism. Exploration of specific key distribution and knowledge propagation mechanisms for specific applications of this protocol may be valuable; see Future Work.

The protocol defines four routines: \textit{Attribute-Authenticate}, \textit{Put}, \textit{Get}, and \textit{Write}.

3.3.1 Attribute-Authenticate

A consumer $C$ negotiates with an authorization node $M$ to authenticate a set of attributes $A$ it would like to use during its session. At the end of a valid negotiation, $C$ receives a $MST$ from $M$.

1. $C$ and $M$ perform $R_{KE}$. All subsequent communication is encrypted using $E_{SYM}$ and authenticated using $MAC$ under the derived key.

2. $C$ sends $A = a_1,...,a_n || V = v_1,...,v_u || TTL_{req} || PK_{self}$ to $M$.

$TTL_{req}$ is a requested TTL for the $MST$; $PK_{self}$ is a public key for the requesting consumer (not tracked by the system).

3. $M$ derives the subset of $A$, $A'$, which it is allowed to authorize.

4. $M$ chooses $expiry$ as the minimum of $TTL_{req}$ and a maximum TTL plus the current time.

5. $M$ generates two random $E_{SYM}$ key-parameter pairs $K_1$, $K_2$ and a random $R$.

6. $M$ computes and sends $K' = \text{Encrypt}_{E_{ABE}}(PK,K_1,(\land_{i=0}^n a_i) \land (\land_{j=0}^u v_j))$ to $C$.

7. $M$ computes $MST_1 = E_{ABE}(K_2,SN \land (\land_{j=0}^u v_j)) || A' || expiry || R || PK_{self}$.

8. $M$ computes $MST_2 = S_{SIG}(MST_1, M_{private})$.

$M_{private}$ corresponds to either the private component of the authorization node’s public-key keypair or the authorization node’s ABE private key, depending on the configuration of the protocol.

9. $M$ computes $MST_3 = \text{Encrypt}_{E_{SYM}}(K_1 || expiry || R,K_2)$.

10. $M$ computes $MST = MST_1 || MST_2 || MST_3 || M_{public}$.

$M_{public}$ is the public key for the authorization node if $S_{SIG}$ is configured as a public-key signature scheme. Otherwise, $M_{public}$ is an indication of the authorization node attribute $AN_{A_j}$ held by the authorization node.
11. $M$ computes and sends $MST' = Encrypt_{ESYM}(MST, K_1)$ to $C$.

12. $C$ decrypts $K'$ to obtain $K_1$ and retrieves $MST$ by decrypting $MST'$ with $K_1$.

When a service node $N$ receives a $MST$, it must verify the validity of the $MST$. A service node $N$ verifies a $MST$ as follows:

1. Validate that the contained $M_{public}$ corresponds to a valid authorization node for the set of attributes $A'$ specified by the $MST$. If $S_{SIG}$ is configured as an attribute-based signature scheme, $N$ simply checks that the specified $M_{public}$ contains $AN_{A_i}$ corresponding to the subset of attributes specified.

2. $N$ validates the content of the $MST$ via the signature.

3. $N$ obtains $K_2$ from $MST_1$ and decrypts $MST_3$ using $K_2$.

4. $N$ then verifies that $R$ and expiry agree between $MST_1$ and $MST_3$.

5. $N$ verifies that the MST has not expired.

3.3.2 Put

A consumer $C$ negotiates with a service node $N$ to persist a new resource in the system.

1. $C$ and $N$ perform $R_{KE}$. All subsequent communication is encrypted using $ESYM$ and authenticated using $MAC$ under the derived key.

2. $C$ sends $N$ a MST.

3. $C$ sends $N$ an identifier for the new resource, an access policy for new resource, and the size of new resource to be transferred.

4. $N$ validates the MST and further validates that the attributes authorized in the MST satisfy the policy specified.

5. $C$ sends encrypted resource content $D$ as $Encrypt_{ESYM}(Encrypt_{ECHAIN}(D, policy), K_1)$, optionally through an encryption proxy, and $SPS_{SIG}(Encrypt_{ECHAIN}(D, policy), SK_{self})$. $SK_{self}$ is the private component of the $PK_{self}$ included in the sent MST.

6. $N$ accepts if and only if the signature verifies.

3.3.3 Get

A consumer $C$ negotiates with a service node $N$ to request a distributed resource $F$.

1. $C$ and $N$ perform $R_{KE}$. All subsequent communication is encrypted using $ESYM$ and authenticated using $MAC$ under the derived key.

2. $C$ sends $N$ an identifier for $F$ and any application-related request parameters.

3. $C$ sends $N$ a MST.

4. $N$ validates the MST and further validates that the attributes authorized in the MST satisfy the policy on $F$.

5. $N$ sends $Encrypt_{ESYM}(Encrypt_{ECHAIN}(F, policy), K_1)$ to $C$.

6. $C$ decrypts using $K_1$ and its private ABE key.
3.3.4 Write

A consumer $C$ negotiates with a service node $N$ to modify a distributed resource $F$.

1. $C$ and $N$ perform $R_{KE}$. All subsequent communication is encrypted using $E_{SYM}$ and authenticated using $MAC$ under the derived key.
2. $C$ sends $N$ an identifier for $F$ and any application-related request parameters (e.g., range to write).
3. $C$ sends $N$ a MST.
4. $N$ validates the MST and further validates that the attributes authorized in the MST satisfy the policy on $F$.
5. $C$ sends modified resource data $D'$ as $Encrypt_{ESYM}(Encrypt_{ECHAIN}(D', policy), K_1)$, optionally through an encryption proxy, and $S_{PSIG}(Encrypt_{ECHAIN}(D', policy), P_{SK})$.
6. $N$ accepts if and only if the signature matches.

4 Analysis

In this section we introduce a general threat model for a distributed storage system utilizing attributes for authentication, authorization, transmission, and storage and discuss the security of the proposed protocol within the framework of this threat model.

4.1 Threat Model

In a distributed storage environment consisting of consumers, authorization nodes, service nodes, and authorities interacting on a basis of attributes, we express a threat model with respect to assets, agents, and adversaries.

Definition 4.1. Asset An asset is any resource accessed, modified, or used via the system, including private keys.

Definition 4.2. Agent An agent is an entity which either actively or passively interacts with the system.

Definition 4.3. Adversary An adversary is an agent who attempts to induce compromise in the system.

Our threat model qualifies security as a distributed storage system’s ability to avoid, prevent, and react to the compromise of concerned assets. An asset is considered compromised if any of the following conditions are met:

- An agent not granted a satisfying set of attributes with respect to an implicit or explicit access policy on an asset gains access, degrading confidentiality of the concerned asset.
- An agent not granted a satisfying set of attributes causes a permanent modification, degrading integrity of the concerned asset.
- An agent granted a satisfying set of attributes is deceived into accepting an asset that has been tampered with, degrading both availability and integrity.

Our model further classifies real and potential compromises according to properties of their consequences and severity.

Definition 4.4. Online-recoverable compromise A compromise is online-recoverable under a protocol if the system may feasibly harden to correct and prevent said compromise without halting system operation.
Definition 4.5. **Local compromise** A compromise is local under a protocol if it may only affect the asset it concerns.

Definition 4.6. **Forward compromise** A compromise is forward under a protocol if it cannot induce additional compromise of resources transferred or held in the past.

Our threat model assumes that an adversary has the ability to eavesdrop and tamper with any communication between agents and that an adversary has substantial computational resources; adversaries may collude and share resources with one another, including compromised assets. We define a weaker definition of this threat model in which the attack surface is restricted solely to the routines and communication defined by the protocol; we define a stronger definition where the attack surface is assumed to be expanded to subsume individual system components, client machines, operators, and network resources, allowing for direct exfiltration of assets as well as insider adversaries and impersonators.

### 4.2 Analysis of Proposed Protocol

In this section, we analyze the given protocol through the lens of the given threat model defined in the previous section. For each attack surface exposed by the protocol, we enumerate and classify risks of compromise conditioned upon the configuration of the protocol.

#### 4.2.1 Attribute-Authenticate

Under the weak threat model, we demonstrate that the Attribute-Authenticate routine is secure with respect to all transferred assets against active and passive attackers, conditioned upon the security guarantees and the collusion resistance of the configured $E_{ABE}$, the chosen plaintext security guarantees of the configured $E_{SYM}$, the guarantees of the configured $R_{KE}$, and the forgery resistance of the configured $MAC$.

Assume first the capabilities of a passive adversary under the weaker definition of the threat model. In the very first step of the routine, the consumer and the authorization node perform $R_{KE}$, and so an eavesdropping adversary is not able to learn anything about the shared key that is used during the routine so long as the guarantees of $R_{KE}$ hold. If an adversary modifies messages sent as a part of $R_{KE}$, he or she induces only a temporary disagreement in the shared key (renegotiation can be performed again), which will be immediately detected by the consumer and authorization node upon integrity verification using $MAC$ so long as $MAC$ is forgery resistant. Thus, conditioned on the guarantees of the configured $R_{KE}$ and the forgery resistance guarantees of $MAC$, there is no risk of compromise of the shared key under the defined threat model.

Because all subsequent communication is encrypted using the derived shared key and authenticated via $MAC$, no eavesdropping adversary is able to gain any information about messages sent so long as $E_{SYM}$ is IND-CPA secure, any modification to message content may be detected by either party so long as $MAC$ is forgery resistant, and corrupted messages may be re-sent and/or renegotiated so long as a communication channel remains open between consumer and authorization node. Conditioned on the chosen plaintext security of the configured $E_{SYM}$ and the forgery resistance guarantees of $MAC$, no asset exchanged during Attribute-Authenticate has a risk of compromise by an active or passive adversary under the weak definition of our threat model.

With regard to Attribute-Authenticate, an active participating adversary would attempt to induce a future compromise by obtaining a MST which authorizes him or her for attributes he or she does not have. Depending on the guarantees of the configured $E_{ABE}$, however, an adversary should not be able to obtain the plaintext of the MST because it is encrypted (under $E_{SYM}$) using a key which is encrypted (under $E_{ABE}$) using an access policy that is only satisfied if the consumer holds all of the attributes advertised. Thus, under the inherent decryption guarantees and the chosen plaintext security of $E_{ABE}$, no adversary may obtain or distinguish a MST for which he or she should not be authorized under the weak threat model. It is also not possible, by means of the collusion resistance of the configured $E_{ABE}$
scheme, that adversarial key holders collude to produce a satisfying $E_{ABE}$ key. As the only asset transferred by Attribute-Authenticate, the MST, is thus secure against both passive and active attackers, we conclude that the attack surface exposed by Attribute-Authenticate is secure under the weak threat model.

**Strong threat model.** Under the strong threat model, we demonstrate that compromise of any asset concerned by the Attribute-Authenticate routine is at the very least forward and online-recoverable.

Consider the capabilities of a worst-case adversary who has gained compromised access to the $E_{ABE}$ private key, the $S_{SIG}$ key-pair, and the $S_{PSIG}$ key-pair during the Attribute-Authenticate routine. As a result of Attribute-Authenticate utilizing $R_{KE}$ without intermediate storage of shared keys, the adversary is unable to re-derive or gain knowledge of non-compromised messages exchanged in the past, conditioned on the guarantees and assumptions of $R_{KE}$; thus, any compromise of the assets held by the authorization node is necessarily a forward compromise. Note that compromise of the $S_{SIG}$ key-pair of a valid authorization node allows an adversary to forge master session tokens, potentially compromising assets exchanged in the other routines of the protocol, meaning that such a compromise is not local. Assuming that some number of system components and at least one authority remain uncompromised, such a compromise is yet online-recoverable, as the protocol admits at least one means of online recovery:

1. Revoke the volatile authorization node attribute bound to forged MSTs by changing its representation and propagating it to all other active system components. This will cause verification of forged MSTs to fail immediately if the protocol uses an attribute-based signature scheme.
2. Blacklist the compromised authorization node and any associated public keys. This will cause verification of the forged MSTs to fail in the case that they are signed using $S_{PSIG}$.
3. Provision a new authorization node having a replacement key for the revoked attribute.
4. Propagate knowledge of the existence of the new authorization node.

Consider now the capabilities of a worst-case adversary who has gained compromised access to the private ABE key held by a valid consumer. Under the Attribute-Authenticate routine, such an adversary may arbitrarily request, receive, and use MSTs he or she should not have. Because illegally obtained MSTs do not allow an adversary to gain knowledge of assets transferred in the past, this compromise is a forward compromise. This compromise is yet online-recoverable, as the protocol admits at least one key revocation mechanism that prevents use of this compromised key:

1. Revoke at least one of the manifest volatile validation attributes associated with the compromised key by changing its representation, presenting knowledge of the new representation publicly. Keys using these validation attributes are thus effectively revoked, as they will not be serviced under the protocol; granularity of revocation is inherently configured by the number of validation attributes used within the system.
2. Re-issue keys with which the re-issued validation attribute is associated.

### 4.2.2 Put

Under the weak threat model, we demonstrate that the Put routine is secure with respect to all transferred assets against active and passive attackers depending on the chosen plaintext security guarantees of the configured $E_{ABE}$, the chosen plaintext security guarantees of the configured $E_{SYM}$, the guarantees of the configured $R_{KE}$, the forgery resistance of the configured $MAC$, $S_{SIG}$, and $S_{PSIG}$.

In the case of a passive third party adversary, for the same reasons as given in our analysis of Attribute-Authenticate, conditioned on the guarantees of the configured $R_{KE}$ and the collision-resistance guarantees of $MAC$, there is no risk of compromise of the shared key under the defined threat model. As in the case of Attribute-Authenticate, because all subsequent communication is encrypted using the derived key and authenticated using $MAC$, no eavesdropping adversary is able to gain any information about messages sent so long as $E_{SYM}$ is IND-CPA secure, any modification to message content by an active third party.
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may be detected by either participating party so long as $MAC$ is forgery resistant, and corrupted messages may be re-sent or renegotiated so long as a communication channel remains open between consumer and service node; thus, no asset exchanged during $Put$ has risk of compromise by an active or passive third party.

With regard to $Put$, a participating adversary may attempt to directly compromise a distributed resource asset by inducing a service node to commit a new resource for which he or she should not be authorized. In order to do so, however, such an adversary would need to present a valid MST. Under the weak threat model, we have shown that such an adversary cannot obtain a usable MST since he or she does not hold the required attributes. In order to coerce the service node to accept a resource in this setting, the adversary would need to forge a MST, which should not be possible, conditioned upon the assumptions and guarantees of the configured $S_{SIG}$ and $S_{PSIG}$. For these reasons, $Put$ is secure from active participating adversaries under the weak threat model.

**Strong threat model.** Under the strong threat model, we demonstrate that compromise of any asset concerned by the $Put$ routine is at the very least forward and online-recoverable.

Consider the capabilities of a worst-case adversary who has gained compromised complete access to a service node, including its $E_{ABE}$ key and stored encrypted data. Within the context of $Put$, such an adversary may either (a) reject or deny service to users, (b) allow spurious writes to data, (c) passively comply with the protocol, further exfiltrating and compromising future versions of the stored encrypted data, or (d) modify stored data. By the nature of this adversary, all data compromised in this scenario is forward compromised: past versions of data or transferred assets are not stored; in addition to this, compromised data is encrypted and yields information only for an individual which holds a satisfying ABE key. Assuming that some number of system components and at least one authority remain uncompromised, such a compromise is online-recoverable, as the protocol admits at least one means of online recovery:

1. Revoke the volatile service node attribute held by the compromised service node.
2. Blacklist the compromised service node and any associated public keys.
3. Provision a new service node having a replacement key for the revoked attribute.
4. Propagate replacement service keys to active service nodes.

Consider now the capabilities of a worst-case adversary who has gained compromised access to the private ABE key, the signature key-pair, or and the MST held by a valid consumer. Under the $Put$ routine, data to be written must be signed using $S_{PSIG}$ and the private key corresponding to $PK_{self}$. Assume first that this adversary has only the MST of a valid consumer. Unless this adversary also has the ability to forge a signature corresponding to the public key $S_{PSIG}$, the service node will reject the put, meaning that control of a MST alone is merely a local compromise, as it cannot induce further compromises without more information, conditioned on the assumptions and guarantees of the configured $S_{PSIG}$. If the adversary does have control of the consumer $S_{PSIG}$ private key, such an adversary would likely also have control of the consumer private $E_{ABE}$ key. In either case, this adversary would be able to write arbitrarily through the service node. As was the case for $Attribute-Authenticate$, this forward compromise is also online-recoverable, as the protocol admits at least one key revocation mechanism which will invalidate both compromised keys and MSTs. If ever only the $S_{PSIG}$ private key is compromised along with the MST, the protocol is self-recovering, as the MST will eventually expire.

4.2.3 **Get**

Under the weak threat model, we demonstrate that the $Get$ routine is secure with respect to all transferred assets against active and passive attackers depending on the chosen plaintext security guarantees of the

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5This protocol may be easily adapted to allow for the system to make use of multiple service node attributes as opposed to one.
configured $E_{\text{ABE}}$, the chosen plaintext security guarantees of the configured $E_{\text{SYM}}$, the guarantees of the configured $R_{\text{KE}}$, the forgery resistance of the configured $\text{MAC}$, $S_{\text{SIG}}$, and $S_{\text{PSIG}}$.

In the case of a passive third party, for the same reasons as given for $\text{Attribute-Authenticate}$, conditioned on the guarantees of the configured $R_{\text{KE}}$ and the forgery resistance guarantees of $\text{MAC}$, there is no risk of compromise of the shared key under the defined threat model. As in the case of $\text{Attribute-Authenticate}$, because all subsequent communication is encrypted using the derived key and verified using $\text{MAC}$, no eavesdropping adversary is able to gain any information about messages sent so long as $E_{\text{SYM}}$ is IND-CPA secure, any modification to message content by an active eavesdropper may be detected by either party so long as $\text{MAC}$ is resistant to forgeries, and corrupted messages may be re-sent or renegotiated so long as a communication channel remains open between consumer and service node; no asset exchanged during $\text{Get}$ has risk of compromise by an active or passive third party.

With regard to $\text{Get}$, an actively participating adversary may attempt to directly compromise a distributed resource asset by inducing a service node to send it data for which it is not authorized. In order for the service node to transfer anything, however, such an adversary would need to present a valid MST. Under the weak threat model, we have shown that such an adversary cannot obtain a usable MST since he or she does not hold the required attributes. In order to coerce the service node to accept a modification in this setting, the adversary would need to forge a MST, which should not be possible given the guarantees of $S_{\text{PSIG}}$. In addition to this, any data which is transferred is encrypted under a policy, and so the adversary would not be able to gain anything from what is transferred unless he or she has also compromised a satisfying $E_{\text{ABE}}$ key.

**Strong Threat Model.** Under the strong threat model, we demonstrate that compromise of any asset concerned by the $\text{Get}$ routine is at the very least forward and online-recoverable.

Consider the capabilities of a worst-case adversary who has gained compromised complete access to a service node, including its $E_{\text{ABE}}$ key and stored encrypted data. Within the context of $\text{Get}$, such an adversary may send requesting consumers corrupt data as desired, exfiltrate encrypted data as desired, or deny service as desired. By the nature of this adversary, all compromises of data in this scenario is forward compromised: past versions of data or transferred assets are not stored. Among information gained would be the MSTs of all valid consumers; however, these have no use without further compromise of the consumer $S_{\text{PSIG}}$ private keys. Assuming that some number of system components and at least one authority remain uncompromised, such a compromise is online-recoverable, by means of, for example, the recovery mechanism described in the case of $\text{Put}$.

Consider now the capabilities of an adversary who has gained compromised access to either the private ABE key, the signature key-pair, or a MST held by a valid consumer. Under the $\text{Get}$ routine, resources requested must be signed using $S_{\text{PSIG}}$ and the private key corresponding to $PK_{\text{self}}$. By the same argument as for $\text{Put}$, only the scenario in which the adversary has further compromised a satisfying ABE key, the consumer private $S_{\text{SIG}}$ key, and the consumer MST yields a compromise; this compromise is a forward, online-recoverable compromise which may be corrected via key revocation or simple MST expiry as described in previous sections.

### 4.2.4 Write

Under the weak threat model, we demonstrate that the $\text{Write}$ routine is secure with respect to all transferred assets against active and passive attackers depending on the chosen plaintext security guarantees of the configured $E_{\text{ABE}}$, the chosen plaintext security guarantees of the configured $E_{\text{SYM}}$, the guarantees of the configured $R_{\text{KE}}$, the forgery resistance of the configured $\text{MAC}$, $S_{\text{SIG}}$, and $S_{\text{PSIG}}$.

In the case of a passive third party adversary, for the same reasons as given in our analysis of $\text{Attribute-Authenticate}$, conditioned on the guarantees of the configured $R_{\text{KE}}$ and the collision-resistance guarantees of $\text{MAC}$, there is no risk of compromise of the shared key under the defined threat model. As in the case of $\text{Attribute-Authenticate}$, because all subsequent communication is encrypted using the derived key and authenticated using $\text{MAC}$, no eavesdropping adversary is able to gain any information about messages sent so long as $E_{\text{SYM}}$ is IND-CPA secure, any modification to message content by an active third party
may be detected by either participating party so long as MAC is forgery resistant, and corrupted messages may be re-sent or renegotiated so long as a communication channel remains open between consumer and service node; thus, no asset exchanged during Write has risk of compromise by an active or passive third party.

With regard to Write, a participating adversary may attempt to directly compromise a distributed resource asset by inducing a service node to commit a new resource for which he or she should not be authorized. In order to do so, however, such an adversary would need to present a valid MST. Under the weak threat model, we have shown that such an adversary cannot obtain a usable MST since he or she does not hold the required attributes. In order to coerce the service node to accept a resource in this setting, the adversary would need to forge a MST, which should not be possible, conditioned upon the assumptions and guarantees of the configured $S_{SIG}$ and $S_{PSIG}$. For these reasons, Write is secure from active participating adversaries under the weak threat model.

**Strong Threat Model.** Under the strong threat model, it is the case that compromise of any asset concerned by the Write routine is at the very least forward and online-recoverable by the same argument as that for the forward, online-recoverability of compromises concerned by Put.

### 4.3 Scalable Security

A major requirement for any scalable storage system is that security is capable of scaling with performance. To analyze the scalability of our protocol, we put forth a framework for quantifying the scalable security of a protocol for a scalable system and further analyze our proposed protocol through this framework.

A measure for scalable security. We define scalable security as the capacity for a system to maintain its instantaneous security guarantees as it scales up or down arbitrarily. To measure the support provided by a protocol for achieving this quality, we introduce a construct which we call security-preserving scaling effort.

**Definition 4.7.** Security-preserving Scaling Effort In a distributed system composed of categories of components $C_1, C_2, ..., C_n$ and a scaling action $A$, the security-preserving scaling effort of $A$ is a function $S_A(\| C_1 \|, ..., \| C_n \|)$ which provides a reasonable asymptotic upper bound on the number of operations required such that the security guarantees of the system before $A$ are the same as those after $A$ completes.

In our analysis of the security-preserving scaling effort of our protocol, we define categories of components $A, AN, SN, C$, respectively representing authorities, authorization nodes, service nodes and consumers. Our analysis focuses on a set of scaling actions restricted to adding or removing an authority, adding or removing an authorization node, adding or removing a service node, and adding or removing a consumer; our scaling effort is defined with respect to the operations of sending messages to a single system component and performing keying operations.

In this section, we demonstrate that our protocol requires a scaling effort linear in the number of authorities for all defined scaling actions except for key revocation, which itself is linear per-revoked key in the number of authorities and authorization nodes.

**Adding or removing an authority.** Our protocol does not involve direct interaction with authorities. With respect to effort required in adding or removing an authority, the effort required by our protocol is bounded by the number of operations required to make active authorities aware of the change, making the change public to some interface to the key distribution mechanism, and potentially deriving a new key for the new authority provisioned.

$$S_A \in O(\| A \|)$$

**Adding or removing an authorization node.** Within our protocol, when an authorization node is added or removed, it must potentially be granted both an ABE key and a public keypair. Because the configured ABE scheme may be multi-authority, it is possible that messages will have to be sent from each authority.
Our protocol further assumes that knowledge of the locations of authorization nodes be made public; this may be achieved in practice by making the change known to some set of public indexes.

\[ S_A \in O(||A||) \] \hspace{1cm} (2)

Adding or removing a service node. Within our protocol, when a service node is added or removed, it must potentially be granted an ABE key. Because the configured ABE scheme may be multi-authority, it is possible that messages will have to be sent from each authority. Our protocol further assumes that knowledge of the locations of service nodes be made public; this may be achieved in practice by making the change known to some set of public indexes.

\[ S_A \in O(||A||) \] \hspace{1cm} (3)

Adding a consumer. As long as a consumer has a public keypair and a valid ABE key, a consumer may interact with the protocol. Thus, to add a new consumer, the only effort required is the generation of a new ABE key the sending of that key to the consumer. In the worst case, the configured ABE scheme is multi-authority, and so messages must be sent from each authority to the new consumer.

\[ S_A \in O(||A||) \] \hspace{1cm} (4)

Removing a consumer. In order to remove a consumer, that consumer’s ABE key must be invalidated. In order to do this, the representation of at least one validity attribute \( v_x \) must be changed, thereby revoking the keys of all consumers \( C \in v \) requiring \( v_x \) to properly authenticate. Keys must be re-issued to all of such consumers. In order for the change to be enforced, the change must be propagated to all active authorization nodes.

\[ S_A \in O(|| v || || A || + || AN ||) \] \hspace{1cm} (5)

5 Future Work

5.1 Implementation

To explore the feasibility and utility of this protocol, we have undertaken the implementation\(^6\) of a simple manifestation of this protocol.

The target system is a simple single-master, many-worker distributed file system in the tone of GFS\(^4\) with a flat namespace and simple access control achieved through an implementation of the protocol described in this work. The specific configuration of the protocol implemented is as follows:

1. Waters08\(^{13}\) as a CP-ABE scheme.
2. A custom extension of Waters08 using AES-256 to achieve variable-length encryption using CP-ABE.
3. RSA-2048 as a public-key signature scheme.
4. AES-256/CBC-MAC for variable-length symmetric-key encryption with MAC
5. Diffie-Hellman as a key exchange routine.

This and future implementations of the proposed protocol will be valuable so as to demonstrate the practical challenges and factors to consider in evaluating different configurations of the given protocol.

5.2 Performance Analysis in Context

The introduction of the devised scheme will undoubtedly affect the performance of the system which uses it. Future work should concern itself with applying the given protocol to existing systems and performing an analysis in performance relative to increased security.

\(^6\)At the time of this work, the partial implementation of this system may be found here: https://github.com/ad-alston/aefs
5.3 Improvement and Standards for CP-ABE

Though the proposed protocol provides a means of addressing the issue of scalable authorization, authentication, and transmission in distributed storage systems, its design, analysis, and implementation suggest areas of exploration relating to both feasibility and utility of CP-ABE schemes. Current schemes are non-standard, varying vastly in performance and complexity; likewise, the lack of maturity of ABE schemes has prevented the appearance of different modes of encryption under CP-ABE schemes. A specific direction for improvement would be the introduction of variable-length encryption modes for CP-ABE, modes desired by the protocol proposed in this work.

5.4 Logging and Compromise Detection

The proposed protocol admits methods for recovering from compromise both internally and externally. When master session tokens or the private keys of users are used to interact with the system, the mechanics of the protocol have a side effect that they generate information at service and authorization nodes about the keys being used in the form of validation attributes. Given some volume of the access patterns for both volatile validation attributes and manifest non-volatile attributes of users, how can the logging and analysis of these access patterns provide additional benefit to the system employing the protocol?

One possible area of exploration involves the detection of and reaction to the compromise of private keys and tokens among users. It may be possible to issue validation attributes on some identifiable basis in order to be able to detect anomalies in key usage. As a simple example, the system may distribute validation attributes on the basis of geographic region. If there is, say, a high frequency of authorization requests from a region in which a certain validation attribute was not issued, the system may be able to infer that keys within that region have been compromised and recover accordingly. Another venue for future work could be the exploration of using the structure and function of validation attributes to trace both traitors and eager attackers: by introducing the equivalent of honey-attributes, it may be possible to detect attempted compromise and/or attempted treason by otherwise valid consumers.

5.5 Coordination and Replication

Many distributed storage systems such as DynamoDB opt for non-centralized architectures that rely heavily on coordination and quorum-like techniques. With respect to the mechanics of the protocol, how might the coordination techniques used by these systems be transitioned to allow for the implementation of mechanisms which make use of coordination among authorization nodes and service nodes? Similarly, what benefits can be offered by these mechanisms?

A direct application of such coordination lies in internal system auditing in systems which employ replication. If a system component is suspicious to an individual user (or other system component), it may be useful for service nodes to vote on the integrity of the state or actions of that component; similarly, if attacks affecting integrity can be identified, coordination among replicas may be used to recover.

5.6 Key Distribution, Knowledge Propagation, and Recovery

Though the analysis of the protocol under the strong threat model defined in this paper identifies that recoveries are online-recoverable, the protocol itself does not directly concern itself with how a system should be adapted to perform online recovery. In the case of key revocation, future work should explore the mechanics of system components responsible for coordinating with the system authority(ies), propagating attribute representation changes, and delivering renewed keys as needed. For recovery in the case of compromised system components, future work should also explore means for a system to provision replacements and segregate those components which have been compromised.

Recent work by Wang et. al. introduces a method of using key homomorphism and secret sharing to achieve a means of key revocation and two-factor authentication [11]. While they propose using this method to reconstruct the master secret key under the used KP-ABE scheme, it may be possible within the scope of our protocol to use this method to devise a secure key distribution mechanism to be
used to reconstruct master secret keys among controlled system components before re-distributing keys. Similarly, key homomorphism may be used within the scope of our protocol as a measure for re-encrypting compromised stored assets without system components gaining knowledge of the asset’s plaintext.

6 Conclusion

In this work, we have introduced a protocol for attribute-based encryption for authentication, authorization, storage, and transmission of distributed resources which addresses the problem of achieving scalable security in distributed storage systems that require fine-grained access control among large numbers of semi-anonymous consumers. We further analyzed this protocol through a general threat model which can be used to analyze the security guarantees of a distributed storage system under these constraints. Through design, implementation, and analysis of this protocol, we have identified future opportunities for exploration admitted by this protocol which additionally allow for internal and external threat detection, automatic recovery, and automated key revocation.

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