City on the Sky: Flexible, Secure Data Sharing on the Cloud

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Abstract—Sharing data from various sources and of diverse kinds, and fusing them together for sophisticated analytics and mash-up applications are emerging trends, and are prerequisites for grand visions such as that of cyber-physical systems enabled smart cities. Cloud infrastructure can enable such data sharing both because it can scale easily to an arbitrary volume of data and computation needs on demand, as well as because of natural collocation of diverse such data sets within the infrastructure. However, in order to convince data owners that their data are well protected while being shared among cloud users, the cloud platform needs to provide flexible mechanisms for the users to express the constraints (access rules) subject to which the data should be shared, and likewise, enforce them effectively. We study a comprehensive set of practical scenarios where data sharing needs to be enforced by methods such as aggregation, windowed frame, value constrains, etc., and observe that existing basic access control mechanisms do not provide adequate flexibility to enable effective data sharing in a secure and controlled manner. In this paper, we thus propose a framework for cloud that extends popular XACML model significantly by integrating flexible access control decisions and data access in a seamless fashion. We have prototyped the framework and deployed it on commercial cloud environment for experimental runs to test the efficacy of our approach and evaluate the performance of the implemented prototype.

Keywords: cloud computing, access control, flexible sharing, fine-grained policies, XACML

I. INTRODUCTION

The emergence of cloud computing in recent years is rapidly changing the way businesses and government agencies, as well as individuals, are storing and managing their data as well as workflows. Instead of developing and maintaining individual data management infrastructures and data sharing mechanisms, data owners now leverage on the cloud services to make their data available to users. The fact that data from multiple sources now reside in one logical place, i.e., the cloud, makes it much easier than ever before to develop large scale applications that require data and knowledge from multiple domains and sources. These applications could include environmental study, city infrastructure planning, disaster monitoring, and many more. In an era when the cloud infrastructure was non-existent, to develop such applications, the developer would have to first talk to individual data owners to specifically provide the data to them, which is likely to involve tedious administration procedures such as signing documents regarding the privileges and responsibilities of each parties, apart from the cumbersome process of actually shipping the data. Then the developer would have to develop software that work with the individual data exchange interfaces/protocols provided by different owners to collect and reformat the data before they could be fed into the applications for analysis or real-time monitoring tasks.

On the multitenant cloud, such data from diverse sources are naturally collocated, making it much easier and much more efficient for the application developers to obtain what they need for their work. More specifically, the storage and data exchange can be handled efficiently by the cloud providers. This means data owners need not worry about how to share, but what and who to share. Putting one’s proprietary data online on the cloud raises concerns regarding data security, privacy and ownership. Even if the cloud service provider is trusted, and legally obliged (through service level agreements and law enforcement) to prevent illegal access of data and information leakage, there needs to be meaningful, comprehensive and flexible ways for the data owners to express their sharing preferences, in a manner which can readily be interpreted and enforced by the cloud service provider. This paper discusses how this can be achieved. One can further argue how this can be realized if the cloud service provider is not even trusted, but that is an issue outside the scope of this work, and is part of our future work.

The objective of this work is to propose and showcase a framework for sharing data on the cloud. The framework, called eXACML, facilitates sharing in an easy-to-use, secure, flexible and scalable manner. For security, we make use of extend XACML [21] — the XML-based and popular framework for access control. XACML has become a standard for specifying and enforcing access control policies. It evaluates requests for resources against a set of policies and returns permit or deny decision, which does not involve accessing any data. In eXACML, we extend XACML to support more fine-grained policies as well as to handle data processing. We demonstrate eXACML’s flexibility by using it in different access control scenarios with different levels of granularity. For usability, eXACML provides an intuitive, easy-to-use interface for data owners and data users to specify and enforce security policies and to access shared data. Finally, we carry out experiments to evaluate the framework performance in a cloud-like environment, the results of which suggests that eXACML is scalable. We motivate our work with scenarios from ongoing works on better city planning, specifically related to weather and traffic information, and the evaluations are also based on datasets, part of which are real, while the rest is synthetic.

In summary, the main contributions of this work are as follows:

1) We demonstrate the needs for secure and flexible data
sharing with practical examples involving city planning and management based on data from weather and traffic monitoring stations. We discuss scenarios in which access control with different levels of granularity of data access are needed.

2) We extend the XACML framework to support fine-grained policies. In particular, fine-grain access control policies (which require data filtering) are expressed within obligations that are passed from the Policy Decision Point (PDP) to the Policy Enforcement Point (PEP), which connects to the database and processes the data queries embedded in the obligations. We refer to this implementation as XACML®. We discuss why this approach could perform better than the traditional approach based on views.

3) We implement a prototype of the framework (eXACML), providing additionally, an easy-to-use user interface. The prototype allows data owners to easily add and modify their policies. Data users can query meta data and details of access policies at remote servers. They can also specify aggregated data from multiple sources in single requests. Responses to data requests contain information of matching policies, enabling flexible conflict resolutions.

4) We evaluate the performance of our prototype in cloud-like settings. Our experiments illustrate that the framework incurs low overhead. We attribute this scalability to the framework’s ability to cache responses and perform aggregation of responses from multiple sources prior to returning them to the data users.

The rest of this paper is organized as follows: Section 2 describes practical scenarios that motivates our framework. Section 3 details our extensions to XACML, followed by the logical design of our framework in Section 4. The prototype and its evaluation are presented in Section 5. We discuss related and future works in Section 6 and Section 7 and conclude in Section 8.

Before proceeding further, we’ll like to make a final note on the scope of the current work and implementation. Broadly speaking, there are two kinds of data - data already stored in the system (which we refer to as archived/archival data), and data stream, where live data is flowing into the system. Likewise, the queries could be ‘on demand’, typically on the stored data, or continuous queries, to be evaluated on the incoming data streams. The current implementation deals with on demand queries on stored data. This is summarized in Table I.

II. MOTIVATING EXAMPLE

As increasing portion of the world population is rapidly moving to the cities, while the resources at our disposal are shrinking at an alarming rate, numerous research and industrial initiatives (e.g., IBM’s smart cities initiative) are focusing in realizing what are being termed as ‘smart(er) cities’ in order to manage resources efficiently at the city scale. Enabling such a move towards smarter cities are cyber-physical systems aggregating data and actuating the necessary resource management actions at the edge, while the necessary data storage and analytics is carried out on cloud based back-end.

In this section, we use some scenarios of road congestion analysis to showcase the need among data owners for flexible data sharing.

A. Settings.

Noticing that one of the major expressways in the city suffers serious congestion during every monsoon season, Singapore’s Land Transport Authority (LTA) has, after preliminary studies, hypothesized that such congestion is mainly caused by three factors, (1) large number of vehicles on the road, (2) slow speed of vehicles, (3) bad weather.

To validate such preliminary conclusions and build a traffic condition model during the monsoon season, researchers need more data. Fortunately, many organizations have been collecting related data: LTA itself has a number of sensors deployed along the road side to record traffic volume, i.e., the number of vehicles passing by at unit time; furthermore, another independent entity, a large local taxi company, collects the speed and location data from their taxis’ GPS devices. At almost any time, there are a number of such taxis running over the whole stretch of the express way. Likewise, the national environmental agency (NEA) has several weather stations deployed close to the congested areas, that record weather parameters such as temperature, humidity, rain rate, etc.

If all these different data owners use a shared cloud infrastructure to store and process the above mentioned data-sets for their individual needs, then when complex analytics involving multiple such datasets become necessary, the data is readily available on the infrastructure thanks to such collocation on the multi-tenant cloud.

Suppose the data are stored in relational tables as shown in Table [1] for traffic volume information, Table [II] for location and speed information and Table [IV] for weather information.

B. Example 1

Suppose that NEA decides to share (possibly for a price) only the rain rate data with LTA researchers, since other weather parameters such as temperature and humidity are not expected to affect traffic condition as much as rainfall does in the context of Singapore, and hence LTA does not want pay for the temperature or humidity information. Furthermore, even if the original collected data available with NEA is for one minute interval, it may want to expose only the data corresponding to five minute averages to LTA. It may also expose the more detailed data to its own employees or to other customers.

The first constraint corresponds to the projection operation in the relational database model and a sample SQL query will
TABLE I: Scope of eXACML, regarding database and query type

| Query/Database      | Archival (relational) databases | Stream databases |
|---------------------|---------------------------------|------------------|
| On demand query     | current implementation          | n/a              |
| Continuous query    | n/a                             | Future work      |

TABLE II: Table TrafficInfo: Traffic volume data from road side sensors

| SamplingTime       | TrafficVolume |
|--------------------|---------------|
| 2011-06-06 10:00:00 | 60            |
| 2011-06-06 10:05:00 | 67            |
| 2011-06-06 10:10:00 | 50            |

TABLE III: Table VehicleInfo: Vehicle speed and location data from GPS devices

| SamplingTime       | Speed (km/hr) | latitude | longitude |
|--------------------|---------------|----------|-----------|
| 2011-06-06 10:00:00 | 100           | x1       | y1        |
| 2011-06-06 10:05:00 | 80            | x2       | y2        |
| 2011-06-06 10:10:00 | 40            | x3       | y3        |

TABLE IV: Table WeatherInfo: Weather data from weather stations

be something like "select RainRate from WeatherInfo". The second constraint can be considered as a sliding window query over a data stream, i.e., the time series rain rate data. Standard SQL does not support these kind of queries well, hence additional operations need to be implemented on top of the RDBMS query engine. To specify a sliding window query on a time series data sequence in our scenario, five parameters are needed, namely, the starting time, ending time, window size, window advance step and aggregation function. The starting time and ending time are the general temporal constraints that specify the segment of the data stream to be returned. The window size and window advance step decide the length of the query window and how fast the window is moving along the data stream. The aggregation function includes numerical functions such as average(), max(), min(), count(), etc., which are applied to the data records to summarize the portion of the data stream within the window.

C. Example 2

Consider that the taxi company agrees to help the researchers by providing their taxis’ location and speed data, but the company only wants to share such information for taxis within some specific regions in the vicinity of the congested areas being studied, instead of exposing the information about its whole fleet, which it deems important business secret not to be exposed to third parties. To enforce such a constraint, a selection operator is applied to the longitude and latitude columns to filter out those records that are not supposed to be shared with the researchers. For the sake of simplicity, assume that this range is specified by a rectangle with the geographical coordinate of the upper left vertex as (a1,b1) and of the lower right vertex as (a2,b2), we can have the corresponding SQL query: select SamplingTime, Speed from VehicleInfo v where v.longitude > a1 and v.longitude < a2 and v.latitude > b2 and v.latitude < b1.

To enable the above access constraints in XACML, we make use of the obligation element in policy element to specify the constraints. Fig. 4 and Fig. 5 present two examples of XACML obligations that embed these constraints. In Figure 4, line 2 indicates that the permission to perform the sliding window query if the decision returned from PDP is ‘permit’. Line 3 indicates that the aggregation function to be used in the sliding window query is average calculation. Lines 5 to 8 specify that starting time is zero o’clock of June 6th, 2011, ending time is zero o’clock of June 7th, 2011, window size is 5 minutes and window advance step is also of 5 minutes. Line 9 indicates that the sliding window is applied on SamplingTime column as well, besides on the actual rain rate data column, which is not shown here within the obligation part. Line 3 in Figure 5 shows the selection predicate to be included in the SQL query to be evaluated on the data table, which only allows vehicle information to be returned if the vehicle’s location is within a
D. Fine-grained Policies

The examples above demonstrate real needs for an access control model that supports fine-grained policies involving fine-grained data processing. At a high level, the models need to be able to express and enforce the following types of policies:

1) Aggregated data: Only results of aggregation functions over raw data such as average, sum, min, max are shared.
2) Trigger-based: a row of data is accessible only if the value of a column satisfies a certain predicate: exceeds a specific threshold, or is contained within a range. As an example, a taxi company is granted access to temperature reading only if the temperature is over 30°C.
3) Sliding window: a sliding window is specified by its starting time, ending time, window size and advance step. Only aggregated data (average, for instance) over the windows are accessible.
4) Approximation: only data whose values approximate those given in the requests are accessible. For example, a request includes a value \( X \), and the policy is specified such that a row of data is returned only if the column \( c \)'s value \( V \) satisfies \( |V - X| < \epsilon \) for some distance function.

We next explore how such fine-grained policies can be flexibly supported.

III. Flexible Sharing Through Fine-Grained Policies

Existing frameworks, such as XACML, do not natively support different levels of granularity to support fine-grained access control. Nevertheless, XACML has emerged in recent years as a mature and widely used model for expressing and enforcing access control policies. Therefore, we extend XACML in order to support fine-grained policies, including those described in Section 2.

For the rest of this paper, we assume relational databases (SQL types) are used for managing data in the back-end. Without loss of generality, but for the purpose of simplicity of exposition, we consider that each database consists of a single table indexed by time values. When requesting for data, the user provides his credentials (for example, name and role) and specifies the location of data. The response contains either a deny decision (i.e., no access to the data), or permit decision together with the returned data as specified in the policies.

A. XACML

XACML is an OASIS framework for specifying and enforcing access control [21]. It is XML based and the latest version is 3.0. XACML allows administrators to control their resources by writing policy files, which are then loaded into a Policy Decision Point (PDP) module. An user wishing to access a specific resource sends request to a Policy Enforcement Point (PEP) where the decision is made by consulting the PDP.

XACML specifies standards for writing policies, requests and interpreting the response.

1) Subjects, Resources and Actions. A subject in XACML has a set of credentials such as its name, role, etc. The subject wishes to perform certain actions (read, write, for example) on a set of system resources.
2) Requests. Request for accessing system resources are written in XML. The subject credentials, system resources and actions are specified in one or more Attribute elements included in the Subject, Resource and Action elements respectively. Fig. [1] shows an example of an XACML request from a subject with role admin to perform read action the temperature column from weather_data database.
3) Policies. A policy contains a Target, a set of Rules each of which has at most one Condition, and a set of Obligations. Multiple policies can be grouped into a policy set, which has its own Target element. The policy is indexed by its Target element, which consists of a number of conditions needed to be satisfied by the request before the rest of the policy can be evaluated. Conditions are essentially boolean expressions over the values included in the request. The policy returns access control decision which is either Permit, Deny, Not Applicable or Intermediate. The last two are used when there is no applicable policy or an error occurred during evaluation. Fig. [2] illustrates an example of an XACML policy that grants access to subjects with government role to the samplingtime and temperature columns of weather_data.

When more than one rules are applicable to a particular request, they are evaluated according to rule combination algorithm specified in the policy. Similarly, multiple applicable policies in a policy set are evaluated according to a specified policy combination algorithm. Examples of combining algorithms (for both policies and rules) are Permit-overrides where a permit policy or rule is evaluated, and First-applicable where the first applicable policy is evaluated.
4) Policy Enforcement Point (PEP). User requests first go through the PEP, which translates them into canonical forms before passing to the PDP. Additionally, PEP also interprets responses and obligations returned from the PDP. In summary, PEP deals with application logics and acts as the access control enforcement mechanism. Our framework extends PEP to provide support for more fine-grained policies.
5) Policy Decision Point (PDP). Data owners’ policies are loaded into the PDP, which evaluates requests received from the PEP against the active policies. Its main task is to efficiently find applicable policies for a given request and to quickly evaluate their rules and conditions to determine the access control decision. It sends back to PEP a well-formed response containing a decision and a set of obligations.
Fig. 1: Example of a well-formed XACML request, in which the user with the role admin requests read access to the column temperature of the database weather_data.

Fig. 2: Example of a well-formed XACML policy which grants access to column samplingtime or temperature of the database weather_data to any subject with role government.
C. Implementations

1) Obligations: Using obligation-based approach, policy writers utilize different types of obligations to specify different database queries. Our current implementation supports four types of obligations (Table V):

| Description       | ObligationId                          |
|-------------------|---------------------------------------|
| Column aggregation| exacml:obligation:column-aggregation   |
| Simple selection  | exacml:obligation:simple-selection     |
| Sliding window    | exacml:obligation:column-sliding-window|
| Approximation      | exacml:obligation:column-approximation |

1) **Column aggregation**: consists of a string attribute with ID exacml:obligation:aggregation-id. The string represents an aggregation function, such as average (Fig. 4, line 2-3), min, max, count or sum.

2) **Simple selection**: consists of a string attribute with ID exacml:obligation:selection-id. The string is a boolean expression that will be used as the WHERE clause when constructing the database query. An example of this obligation is shown in Fig. 5, in which the policy restricts access to data to within a certain geographical region.

3) **Sliding window**: we assume that the column from which the sliding windows are based is of type DateTime (although sliding windows could be constructed from any other sortable types). The obligation consists of a number of attributes:
   - Sliding window column: string attribute with ID exacml:obligation:sliding-window-column-id specifies the column of type DateTime from which sliding windows are constructed.
   - Start and End: time attributes with IDs exacml:obligation:sliding-window-start-id and exacml:obligation:sliding-window-end-id respectively.
   - Window size: integer attribute with ID exacml:obligation:sliding-window-size-id specifies the window size (in hours).
   - Advance step: integer attribute with ID exacml:obligation:sliding-window-step-id specifies how the sliding window advances, i.e., the number hours between starting time of two consecutive windows.

Fig. 4 (line 4-10) shows an example of a sliding window based on SamplingTime column. The window’s size is 5 hours, starting from 2011-06-06 00:00:00, advancing in 5-hour steps until 2011-06-07 00:00:00.

4) **Approximation**: this obligation specifies the acceptable distance between the column values with respect to the values included in the request. Attributes containing column IDs are specified in both the requests and the policies. Specifically:
   - In the request: string attribute with ID exacml:obligation:approximation-param-id is of the form 
     `<columnId>:<value>` which represent the value of the specified column.
   - In the policy: string attribute with ID exacml:obligation:approximation-param-id
contains the column IDs. Columns specified in the requests must be a subset of what is specified in the policies. Also required is a double attribute with ID

\[
\text{exacml:obligation:approximation-value-id}
\]

which represents the distance between the vector of column values in the database and that included in the request.

2) Handling obligations.: PEP extracts attributes embedded in the obligations and constructs corresponding queries to be executed on the database. It is not uncommon for a policy to have more than one types of obligations, which allows for more expressive, fine-grained conditions for accessing data. Essentially, PEP creates queries of the following form:

\[
\text{select } f(\text{column}_1), f(\text{column}_2), \ldots, f(\text{column}_n) \\
\text{from Table_name where Where_Condition}
\]

(1)

where \( \text{column}_i \) \((1 \leq i \leq n)\) and Table_name are extracted from the Resources element of the request. When no obligation is returned, \( f \) and Where_Condition are set to empty strings. In this case, the query becomes:

\[
\text{select column}_1, \text{column}_2, \ldots, \text{column}_n \\
\text{from Table_name}
\]

PEP obtains \( f \) from the string attribute in the column aggregation obligation. When a simple selection obligation is returned, Where_condition is taken directly from its string attribute. For approximation obligations, the PEP first retrieves a vector of values from the request, namely \((x_1, x_2, \ldots, x_k)\) from columns \( c_1, c_2, \ldots, c_k \). It then obtains the distance value \( \delta \) in the obligation, and sets Where_condition as:

\[
\sqrt{(c_1 - x_1)(c_1 - x_1) + \ldots + (c_k - x_k)(c_k - x_k)} < \delta
\]

Handling sliding-window obligations are more complex. First, the tuple \((\text{start}, \text{end}, \text{window size}, \text{advancing step})\) are extracted from the obligation. The total number of windows are:

\[
nW = \left\lfloor \frac{\text{end} - \text{start} - \text{window size}}{\text{advancing step}} + 1 \right\rfloor + 1
\]

For every window, PEP creates a different query. More specifically, let \( c \) be the column (of type DateTime) from which the sliding windows are constructed, a query \( i \) \((0 \leq i < nW)\) is of the form:

\[
\text{select } f(\text{column}_1), f(\text{column}_2), \ldots, f(\text{column}_n) \\
\text{from Table_name where Where_Condition} \\
\text{AND } c \geq \text{start+step*i} \text{ AND } c < \text{start+step*i+size}
\]

where Where_Condition are constructed from simple selection and approximation obligations.

IV. THE LOGICAL FRAMEWORK

This section presents our design of the framework that enables secure, easy-to-use, flexible and scalable data sharing. The security comes from the use of XACML for specifying and enforcing access control. The flexibility property is the result of our enhancement to XACML which supports a wider range of access control policies. Usability and scalability are achieved through a simple client interface and the use of a proxy server, whose details are described below.

A. Entities

Fig. 6 illustrates the main entities and how they interact in our framework. Clients consist of data owners who wish to share and enforce access control on their datasets, and of data users who are interested in accessing the data. A data owner can have more than one datasets and a data user can request access to multiple datasets. Databases are database servers which manage clients’ datasets. Access to the database is controlled by at least one instance of XACML* (discussed below). These servers are likely to be remote and maintained by a third party (cloud) provider.

Our framework — eXACML — is positioned in between clients and databases (Fig. 6). Its roles are to mediate their interactions and to safeguard the databases. Essentially, eXACML is made up of a client interface, a proxy server, cloud servers and XACML* instances.

- Clients interact with the databases through a local client interface that parses inputs into request messages and forwards them to the proxy server. It waits and interprets response messages before returning them back to the clients. This interface abstracts out the complexity of exchanging well-formed messages with the proxy server. It allows clients to share and query data in an intuitive manner.

- A cloud server (or server), usually located in the same machine as the databases, accepts and processes client requests. We will refer to this component as server. It manages and responses to meta queries concerning XACML* instances. For data requests, it forwards them to the appropriate XACML* instances and sends the results to the proxy in well-formed messages.

Fig. 6: eXACML framework. XACML* denotes the extended XACML described in Section 3.
Fig. 4: Obligation portion of the XACML policy for Example II-B

Fig. 5: Obligation portion of the XACML policy for Example II-C

- XACML* is an implementation of the extended XACML model described in Section 3 (Fig. 3). It processes data requests (received from the cloud server) by first asking PDP for the access decision. If permitted, it executes the obligations, which involves querying the database. The result is forwarded back to the cloud server.

- Communications between clients and servers go through a proxy server (or proxy). It processes requests from clients before forwarding them to the servers, and combines the results into client response messages. As an example, suppose a request from a data user requires accessing data from multiple datasets, the proxy first creates multiple requests and sends to the corresponding servers. It waits for all the responses from servers, then combines the results into a single response message for the data user.

The benefit of having the proxy server is two-fold:

1) **Improved performance**: Combining data before returning to the users reduces communication costs. Caching at the proxy can also improve response time and reduce both computation and communication costs for the database servers. We demonstrate this effect in the evaluation section.

2) **Additional level of abstraction**: The proxy server acts like a DNS service mapping datasets into global, easy-to-remember names, achieving network data independence, which makes it easier for clients to manage and query data.

B. Trust and Data Model

We assume cloud servers and the proxy server are honest. This means that they are trusted to run the correct, latest eXACML framework. They are also trusted not to violate data privacy. More specifically, the proxy is trusted not to tamper with the data received from database servers, and not to violate data privacy. The only adversaries are rogue clients who can collude in attempt to gain unauthorized access to the datasets belonging to honest data owners. We remark that these assumptions (particularly, that of trusted service providers) are reasonable since cloud service providers are striving to gain reputation to run their business, and furthermore have legal obligations based on Service Level Agreements [23].

We assume that datasets are managed by relational database systems. For simplicity, each data owner has at most one dataset. This assumption can be relaxed by virtualizing the data owner, so that it has multiple identities, each of which possesses a different dataset.

C. Cloud Model

We now discuss different ways to connect the database, XACML* and cloud server components. As seen in Fig. 6 the
number of servers, the number of databases and XACML* instances do not have to match. In particular, multiple databases may share the same XACML* instance, while a cloud server may handle multiple XACML* instances.

A server represents a logical, addressable machine to which the proxy connects. One server can handle requests for multiple datasets, but we assume each server is connected to one dataset. This assumption is reasonable since each data owner has at most one dataset, and it is likely that data owners use independent virtual machines.

Next, we consider the question of how XACML* instances are shared among databases. At one extreme, a single XACML* instance is sufficient to deal with all access requests. In this case, the servers connect to the the same XACML* instance, and policies are added to the same PDP. The PEP has access to multiple databases at different machines. However, this approach introduces a single point of failure, and data owners may prefer to have their access control systems separated from each other. Moreover, extra layers of authorization is required to prevent rouge clients from uploading policies associated with datasets of honest data owners. At the other extreme, the server maintain one XACML* instance per dataset. Since data requests can be processed in parallel, this approach could lead to significant improvement in performance. However, a potential drawback is the overhead in maintaining a large number of XACML* instances, especially if many are idle.

When multiple datasets share the same physical machine (but are in separate virtual machines), it makes more sense for them to share one XACML* instance. This approach benefits from the parallelism in processing requests, while having reduced overhead in maintenance. However, sharing an XACML* instance experience the same problem with single point of failure and extra layer of authorization as with a single XACML* instance.

Considering the above trade-offs, in this paper, we finally adopted the simple, no-sharing approach, i.e. one server connects to one XACML* that safeguards one database (illustrated in Fig. 7). This model does not require another layer of authorization and therefore is easy to implement.

D. One or Multiple Proxies?

Having multiple proxies addresses the trust problem associated with a single proxy. It could also improve client throughputs, since requests can be processed in parallel. However, joining data — one of the proxy’s main features — across multiple proxies is more complex. Since proxies also maintain data caches, a mechanism for cache coherence among distributed servers is also required. Therefore, trade-offs between efficiency and maintenance overhead must be carefully considered. Our current framework employs only one proxy. We defer the protocols with multiple proxies for future work.

E. Initialization

In the beginning, a data owner creates a database for its datasets and initializes an XACML* instance at a remote data server. The XACML* instance starts with an initial policy specifying who can add and remove data and policies. This process is done by invoking

\[\text{success, fail} \leftarrow \text{initDatabase}(\text{host}, \text{port}, \text{dataID}, \text{databaseType, credentials})\]

where host, port are the address of the server, dataID is the unique identifier of the dataset, databaseType is name of the database management system (MySQL, for example), and credentials consists of the data owner’s name, role and other authentication information for accessing the server. The client interface wraps these parameters into a message forwarded to the proxy, then sends it to the specified server. After authenticating the data owner, the server creates the database, starts an XACML* instance and connects its PEP to the database. Finally, the server uploads a root policy to the newly created XACML* instance. The root policy specifies that only users with credentials can add new data, upload new and remove existing policies. This policy prevents other clients from adding their own policies to this XACML* instance.

If successful, the proxy creates a new mapping from dataID to the dataset, as explained next.

F. Data and Policy Management.

Once a database is initialized successfully, it can be identified uniquely by its dataID. The proxy maintains a mapping dataID_to_desc, which is a list of:

\[\text{dataID:<host, port, database name>}\]

All client requests contain dataIDs. The proxy resolves locations of the dataset using its mapping, before forming new requests and forwarding them to the appropriate database servers.

a) Adding and removing data.: To add or remove new data from a dataset, the data owner invokes

\[
\text{success, fail} \leftarrow \text{addData(data file, dataID, credentials)} \\
\text{success, fail} \leftarrow \text{removeData(remove query, dataID, credentials)}
\]
where data file contains data to be added to dataID using the given credentials. remove query is the query to remove records from the database. The client interface sends a request to the proxy, which in turn constructs and forwards a well-formed XACML request together with the file hash or query hash to the server. The server keeps the hash as the pending add or pending remove token. Only if the access control decision is 'permit' does the client interface sends data file or remove query to the server, which verifies that the content hash matches with the pending add or pending remove before performing the query. In this protocol, the hash value is used to prevent other data owners from adding rogue data or remove unauthorized data.

b) Loading and removing policy.: Every loaded policy is identified uniquely by its ID of the form dataID:policyID where policyID is the integer index of the policy. The XACML* instance maintains an index counter which advances whenever a new policy is added. To add or remove a policy, a data owner invokes

\begin{verbatim}
{policyID, fail}
\end{verbatim}

\begin{verbatim}
<- loadPolicy(policy file, dataID, credentials)
\end{verbatim}

\begin{verbatim}
{success, fail}
\end{verbatim}

\begin{verbatim}
<- removePolicy(policyID, dataID, credentials)
\end{verbatim}

where policy file contains the XACML file to be uploaded to dataID using the given credentials. The policy to be removed is identified by the tuple (dataID, policyID). The client interface forwards a request to the server, which processes a well-formed XACML request (for loading or removing policy) using dataID and the credential. Once at the server, the request is evaluated by the appropriate XACML* instance. Only if the decision is permit is the policy file added or the policy dataID:policyID is removed from the corresponding PDP. In case of policy addition, the new policy ID — the current index counter's value — is forwarded back to the data owner. We assume that policy is small, thus there is no need for the 2-step protocols as in adding and removing data.

c) Querying policy.: Both data owner and the server keep track of the policy IDs associated with the database. One can query about the loaded policies for a dataset, using

\begin{verbatim}
{{(policyID, description)}, fail}
\end{verbatim}

\begin{verbatim}
<- queryPolicy(dataID, credentials)
\end{verbatim}

which returns a set of tuples (policyID, description) where description is the Description element of the corresponding policy.

G. Data Request.

A data user issues a request for data through the client interface. The request may involve accessing multiple datasets. The data user knows dataIDs, but may not know of the detailed structure of the datasets.

1) Querying meta data.: A data user can issue a query for the dataset’s meta data prior to requesting the raw data. Typical meta data includes table names and schemas. Data owners can restrict access to such information through a set of policies. To query meta data, the data user invokes:

\begin{verbatim}
{(tableID), fail}
\end{verbatim}

\begin{verbatim}
<- queryTables(dataID, credentials)
\end{verbatim}

\begin{verbatim}
{(columnID, type), fail}
\end{verbatim}

\begin{verbatim}
<- queryColumns(dataID, tableID, credentials)
\end{verbatim}

The proxy translates the client request into a well-formed, standard XACML request in which the Action attribute is set to show_table or show_column respectively. If the PDP returns a permit decision, the PEP retrieves and returns the database's metadata accordingly. The result for queryTables (if permitted) is a set of tableIDs, which can later be used in requesting raw data. The result for queryDataScheme is a set of tuples (columnID, type) representing the column name and type.

2) Querying data.: Clients can request data by invoking:

\begin{verbatim}
{(data record), (matching policies), fail}
\end{verbatim}

\begin{verbatim}
<- queryData(requested resources, joining condition)
\end{verbatim}

where

\begin{verbatim}
requested resources
\end{verbatim}

\begin{verbatim}
= {<credentials, dataId, {columns}, {actions}, {constraints}>}
\end{verbatim}

represents the resources requested from different datasets. joining condition specifies how the results from those datasets are joined. These results are returned separately if joining condition is null. constraints contains conditions that are applied to the returned data. For example, column_i > \theta where \(\text{column}_i \in \{\text{columns}\}\) indicates that the request is only for data whose \text{column}_i values are greater than \(\theta\). The protocol proceeds as follows:

1) For every requested resource, the proxy creates a well-formed XACML request using dataID, columns as Resources and actions as Actions attributes. The request is then forwarded to the server specified by dataID.

2) The XACML* instance returns access control decision, the accompanied data (if decision permitted), and IDs of the matching policies.

3) The proxy, on receipt of non-empty data, applies conditions specified in constraints. Depending on the value of joining column, it performs data joining (discussed next) before sending the final response to the client.

H. Data Joining.

The joining condition parameter used in queryData specifies how the results are joined before returning to the client. In particular:

\begin{verbatim}
joining condition \in \{null, \{c_1, c_2, ..., c_k\}\}
\end{verbatim}

where \(k\) is the number of requested resources and \(c_i\) (\(1 \leq i \leq k\)) are the joining columns of the returned data. When joining column = null, the proxy forwards what it receives from the server directly back to the client. Otherwise, it waits until getting data from all requested servers, then constructs a client response by joining the results using normal database join operations.
I. Conflict Resolution.

It is possible for clients to receive empty data for their requests, especially when the requests involve more than one datasets. This arises because different policies associated with different datasets are enforced. We refer to this as policy conflict, which happens in one of the two cases:

1) There is at least one policy that denies the client’s access.
2) All policies permit access, but the joined data still results in an empty set. For example, one policy allows access to data where column $i > \theta$ whereas another policy allows access to data where column $i \leq \theta$. Another example is when two policies specify different sliding windows, as a consequence the joining columns do not have values in common.

We provide a simple mechanism for dealing with policy conflict. Responses from queryData includes IDs of the matching policies. When conflict occurs, the client is aware of the cause and is able to contact the dataset owner to resolve the conflict. We assume that such resolution is done out-of-band and is not within the scope of the framework.

J. Caching.

The proxy maintains a cache of data received from the servers. Since operations in the cloud server are slow, especially when involving database access, caching can improve the response time. It is also reasonable to expect a cache-friendly request pattern from clients, as popular data are frequently requested.

We consider a simple design, in which data cache is the map $\langle$request$>:\langle$data$\rangle$ where request is the XACML request with the corresponding data.

- **Cache replacement**: when full, an old entry is evicted in a random fashion.
- **Cache coherence**: stale entries can lead to security violation. For instance, a new policy update denies a client access to a dataset, but the cache contains data of previous access which will be served by the proxy at the client’s next request. We address this problem by simply purging entire cache every time a policy is loaded or removed.

V. Prototype and Evaluation

A. Prototype

We have implemented a prototype of eXACML, which consists of over 3400 lines of Java code. Database accesses are provided by JDBC API, while communications between clients, proxy and servers are done through Socket interface. For XACML*, we extended Sun’s XACML implementation [28] — an open source, Java project that supports XACML 2.0 standard. We instrumented its PEP module to handle more obligations (Section 3). The prototype supports all the features discussed in the previous section: a client is able to load, remove, query data and policies.

Our prototype provides an easy-to-use graphical interface for querying and managing data. A query form (Fig. 8(b)) takes in user credentials and requests. A response from the server includes the data server information, matching policies...
and the data (if applicable), which are displayed in the data view window (Fig. 9). Policies are updated and queried using similar GUI, as shown in Fig. 9.

B. Evaluation

We evaluated our prototype’s performance, and its ability to support dynamic, fine-grained access control policies. The system performance is measured by the time taken to fulfill user requests. We compare our prototype’s performance against that of a direct-query system, i.e. without the access control layer. We refer to the later as direct-query system.

1) Methodologies:

a) Setup.: We emulate a cloud-like environment running our prototype, as shown in Fig. 9. More specifically, we make use of four machines, two running servers, on running the proxy and the other represents a client. The machines belong to the PDCC cluster each has one Xeon processor 3.0Ghz, running OCSS5.1 (2.6.18-53El5smp) operating system with 4GB of RAM. The machines are connected via InfiniBand 20Gbps.

The servers maintain two databases: a weather database and a traffic database. The former contains four tables with real data taken from four different weather stations collected in a 5-day duration and with one-minute sampling interval. We synthesize the traffic database with two tables containing records of traffic volume and vehicle speed that match with the weather datasets.

b) Workloads.: We generate synthetic workloads that include large numbers of policies and requests. Since our prototype is compared against a direct-query system, the workloads also contain a large number of direct database queries, each corresponds to a request in our prototype. A direct query is forwarded to the server, which executes and returns the same data as when executing the corresponding request in our system. The parameters used in generating workloads are shown in Table. 7. The workloads and source code for generating them can be found at http://sands.sce.ntu.edu.sg/trac/exacml/

First, we use nDirectQueries and directQueryDist to create a set DQuery of direct queries of five different types: selection, approximation, aggregation, sliding window and data joining. The first three types are ordinary database SELECT query, which is forwarded by the server directly to the database engine. Sliding window queries are first converted into multiple SELECT queries, one for every window, which are then sent to the database engine. Data joining queries contain two sub-queries (of the other four types) chosen at random and for different data servers. Each data server processes and returns the result independently. Next, nPolicies unique XACML policies are generated, each with different exacml:subject:role-id. Every policy corresponds to a direct query whose type is either selection, approximation, aggregation or sliding window. Therefore, the set of policy obligations and DQuery represent the same set of SELECT queries to be executed by the database engines.

Next, we generate a set of requests. For every policy, we construct one matching and one non-matching request. The matching request contains credentials, resources and actions as specified in the policy. For the non-matching request, we use a different exacml:rbms-database-id from the weather and traffic database names. For each data joining direct query, we create corresponding (matching and non-matching) requests made up of two sub-requests. Each sub-requests from the matching request corresponds to a sub-query in the data joining direct query. In summary, a matching request executed in our prototype returns the same data as the corresponding query evaluated in the direct-query system.

Finally, we create a workload of nRequests requests following Zipf distribution with skew parameter α. This workload models a realistic use of the prototype, in which a small number of popular data are requested frequently. Such request pattern is found in many other systems, such as P2P file-sharing and web caching [3], [16]. We select maxRank unique queries from DQueries at random, then assign them with random ranks. A sequence of queries is generated from the selected set with Zipf distribution, using α = 0.223 (as in [16]). For every direct query, this workload also contains the corresponding policy, matching and non-matching request.

2) Metrics.: In the following experiments, we investigate our prototype’s effectiveness in granting data access to authorized requests and denying unauthorized ones. We also measure its performance in terms of the time taken to fulfill authorized data requests. This is compared against the direct-query system, i.e. one without eXACML. We also provide quantitative analysis of the proxy, especially its caching and data joining features.

3) Experiments and Results.: We first load nPolicies unique policies onto the data server. The measured time is reasonably small, with mean of 0.034s and standard deviation of 0.016 per loading operation.

We then run two sets of experiments:

1) The workload consisting of nDirectQueries unique queries and the corresponding unique requests. We enable the data joining option at the proxy in the first run, and disable it in the second. To disable cache, we simply change the proxy configuration file. To run without the joining option, we re-generate the workload without data joining queries and requests. We measure the time taken to fulfill direct queries and data requests.

2) The workload contains nRequests queries and the corresponding requests, which follow the Zipf distribution.

In both experiments, non-matching requests are denied access. Fig. 10 and Fig. 11 compare the performance of our prototype against direct-query system, using measurements of matching requests. In both figures, there is a number of requests taking over 5s to finish. They are sliding window requests, which translates into a large number of SELECT queries to be executed by the database engines. That the server needs to wait and aggregate the results into a single client message, and that JDBC implementation incurs non-significant overhead for executing a SELECT query both contribute to the noticeable delay.
Variable | Value | Description
---|---|---
nDirectQueries | 1000 | number of direct queries
DirectQueryDist | 248:248:248:156:100 | distribution of direct queries (selection:approximation:aggregation:sliding window:joining request)
nPolicies | 900 | number of unique policies
nRequests | 1500 | number of matching requests
α | 0.223 | skew parameter for Zipf distribution
maxRank | 300 | maximum rank of unique requests from which Zipf distribution is generated

TABLE VI: Summary of parameters used in setting up experiments

Fig. 10: Overall performance, with vs without exacmlXACML. Caching and joining options are on

Zipf distribution, eXACML performs better most of the time (up until the 89th percentile). This is thanks to the caching mechanism at the proxy, whose benefit will be analyzed in more detail later.

Fig. 11 shows how the overhead changes when the proxy performs neither caching nor data joining. The overhead is more discernible: for unique requests, the overhead starts from 20th percentile, as compared to 45th percentile in Fig. 10. Similarly, for queries following Zipf distribution, the overhead is seen from 10th percentile, as compared to 89th percentile in Fig. 10. This implies that caching and data joining at the proxy are most effective when the query distribution is heavy-tailed.

We proceed to analyze benefits of caching at the proxy. Request times for Zipf-distribution queries with and without cache are extracted from the experiments and plotted in Fig. 12. We show the results with and without data joining queries. In both cases, caching results in better performance. By itself, i.e. without the joining data feature, caching leads to 50% improvement for more than 80% of the requests. For the workload including data joining queries, a similar pattern can be seen, although the improvement is not as noticeable.

Finally, we analyze the benefit of the data joining feature at the proxy. We run the same experiments as before, but with workloads consisting of only data joining queries and requests. The results shown in Fig. 13 are for both unique and Zipf-distribution requests. It can be seen that eXACML outperforms the direct-query system up until 65th percentile for unique queries and 70th percentile for Zipf-distribution queries. This is because for most requests, eXACML helps reducing the
Fig. 13: Benefit of proxy performing data joins. All queries require data joining

data size substantially (by joining the results from two servers) before transferring it back to the client. In contrast, without eXACML, the client has to wait for all data to come back individually before performing joining by itself. Notice that some requests in eXACML still experience longer delay (after 70th percentile), because extra communication between client and proxy (as opposed to the direct communication between client and server) and computation overhead at the proxy are not fully discounted.

VI. RELATED WORK

There exists cloud-based systems that enable data sharing from multiple sources. SenseWeb [26], SensorBase [10] are examples of cloud services that let users upload and share their sensor data. They support coarse-grained access control model in which an user either makes its dataset public, shares it with a list of collaborators or keeps it private. Similarly, Google’s Fusion Table [14] allows user to upload generic data and to perform simple analysis such as data visualization on the cloud. Recently, companies such as Okta [22] have started implementing cloud-brokerage models that provide centralized service for management of enterprises’ resources, including access control. However, these access control model is also coarse-grained, which means it cannot deal with the access scenarios we consider in this paper. In addition, data owners in these systems upload their datasets onto a centralized cloud, whereas our work does not make such assumption (we consider multi-cloud environment in which different data owner uses its own cloud provider).

There are also numerous works focusing on access control and data privacy on the cloud. Airavat [27], for example, assumes the cloud is trusted in enforcing access control. It uses a simple mandatory access control system available in SELinux [11], and provides a trusted environment for executing MapReduce [11] jobs while guaranteeing differential privacy [12]. Our work makes the same assumption about cloud’s trustworthiness, but aims at improving the access control aspect of the system, which is complementary to Airavat. Other works [29], [15], [23] assume the cloud is untrusted and employ cryptographic approach for access control. In [29], data is encrypted with attribute-based encryption [13], [7] by a proxy using a proxy re-encryption technique. Embedded in the ciphertext are conditions that must be met when decrypting. Plustus and CloudProof [15], [23] use broadcast encryption [19] to protect the data, while key management [15] is done using key rolling and lazy revocation techniques. These cryptographic approaches provide strong guarantees for data security, but they cannot express fine-grained access control policies as described in our work. Thus the focus in these works is also complimentary to ours. In addition, key management and revocation protocols are complex and incur much overhead in such an untrusted environment.

Multiple policies matching in XACML is usually resolved by the top-level policy combining algorithms. XACML supports only a limited number of combining algorithms. Ninghui et al. [20] and Rao et al. [25] propose a formal language for expressing more fine-grained policy composition. The language can deal with evaluation errors and combining of obligations. Mazolineni et al. [17] propose a method for combining policies based on their similarity and users’ preferences.

Time-series data — similar to those considered in our paper — could arrive at the system in continuous streams, for which relational databases such as MySQL and Postgresql are not ideal. Aurora [2] is a popular data stream management system that addresses limitations of relational databases when it comes to stream data. Carminati et al. [9], [8] are among the first to propose a model and implementation of access control for data streams based on Aurora. The model supports four access scenarios: column-based, value-based, general window and sliding window. Our framework supports all of these scenarios for on-demand queries over archival databases. The extension to eXACML that deals with continuous queries over stream databases is left for future work.

VII. FUTURE WORK

We have implemented a simple prototype and carried out preliminary evaluation of our framework. The next step would be to improve the prototype and perform more comprehensive evaluations. More specifically, the cloud-like environment set up in the experiment contains only two data servers. In addition, only one dataset comes from real monitoring stations, and the workloads are synthetic. Therefore, we plan to acquire more realistic datasets and workloads, and to evaluate the prototype with larger numbers of data servers. We also plan to export our prototype into real cloud environments such as Amazon EC2 and Microsoft’s Azure [4], [18], and benchmark it with real data mining applications accessing real datasets.

We assumed that each dataset is guarded by an independent XACML* instance. We have acknowledged the trade-offs in having multiple datasets sharing one XACML* instance, especially when datasets reside in the same physical machine. Another trade-off is the number of proxy servers. It would be interesting to investigate these trade-offs further by extending the framework with XACML* sharing and distributed proxies.

As shown in Table 1, eXACML only deals with archival databases and queries. The immediate extension will be to

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**Figure 13:** Benefit of proxy performing data joins. All queries require data joining.

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**Table 1:**

| Scenario       | Time (s)  |
|----------------|-----------|
| Unique queries, direct | 0.1       |
| Unique queries, pCloudXACML | 0.2       |
| Zipf-distribution, direct | 0.3       |
| Zipf-distribution, pCloudXACML with cache | 0.4       |
support stream databases and continuous queries. Relational databases are not the best tool for handling stream data, for which other models have been proposed [2]. We will examine the design and compare performance of the extended eXACML to that of the existing works on access control for stream data [9, 8].

Regarding data sharing, access control only addresses the problem of authorization. We have so far made an assumption that authentication is implicit, that is, clients are given static credentials and the servers always accept the given credentials. We plan to incorporate an authentication model into our framework. It is an interesting challenge in decentralized settings, of which our multi-cloud scenario is an example, since authentication may depend not only on static credentials but also on previous interactions between parties and the states of the entire system. Authentication is also an important when the cloud provider has to log and notify data owners of access to their data (for billing purposes, for example). We plan to use other access control languages such as DynPal [9] or SecPal [5], because they are more suitable for handling dynamic authentication than XACML.

Finally, we have always assumed the cloud is trusted in enforcing access control policies and not to violate user’s data security and privacy. However, users with sensitive data or data that have been expensive to collect will demand highest level of security. As a consequence, they cannot assume the cloud is trusted in handling their data. Existing works have taken the cryptographic approach that encrypt data and attempts to outsource the key management to the cloud. Nevertheless, the range of access control policies supported by the existing systems has been limited. For future work, we aim to find practical cryptographic protocols that can handle more fine-grained access control scenarios. Since eXACML contains two components belonging to third parties: the proxy server and the cloud servers, we will investigate relaxing the trust assumption for these components one by one.

VIII. CONCLUSION

In this paper, we have proposed a framework (eXACML) that allows users to share their data on the cloud in a secure, flexible, easy-to-use and scalable manner. We considered a trusted cloud environment, in which data are maintained in relational databases. The cloud environment makes it easy for data owners to share and benefit from mining the aggregated data. The main challenge is how to let users control access to their data in most flexible ways. We achieved security and flexibility by extending the XACML framework, allowing users to specify fine-grained access control policies. Our framework contains a proxy server residing in between clients and the cloud servers. It processes requests from the clients, joins and caches responses from the servers before sending back to the client. We have implemented a prototype and carried out preliminary experiments to evaluate its performance. The results suggested that the framework is scalable, as the overhead incurred is small, thanks to the caching and data joining features at the proxy. In addition, the prototype provides a graphical user interface that lets users share and manage their data in an easy-to-use manner.

We believe that in order to take full advantage of cloud computing, having a framework such as ours is very important. Our paper has taken the first steps towards realizing a practical and usable sharing-friendly cloud environment. We have also identified many avenues for future work, such as improving scalability with more proxies, adding support for stream data and other policy languages, and relaxing assumptions on the trustworthiness of the cloud.

a) Acknowledgments.: This work has been supported by A*Star TSRP grant number 1021580038 for ‘pCloud: Privacy in data value chains using peer-to-peer primitives’ project. The authors will like to thank Dr. Lim Hock Beng for providing access to the weather data sets used in some of the experiments.

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