Elastic Extension Tables for Multi-tenant Cloud Applications

Haitham Yaish[1, 2, 3], Madhu Goyal[1, 2], George Feuerlicht[2, 4]

[1] Centre for Quantum Computation & Intelligent Systems

**[2] Faculty of Engineering and Information Technology,
University of Technology, Sydney
P.O. Box 123, Broadway NSW 2007, Australia**

**[3] Faculty of Engineering,
American University of the Middle East, Kuwait**

**[4] Faculty of Information Technology,
University of Economics, Prague, Czech Republic**

haitham.yaish@uts.edu.au, madhu@it.uts.edu.au, george.feuerlicht@uts.edu.au

***Abstract*—Software as a service (SaaS) is a Cloud Computing service model that exploits economies of scale for SaaS service providers by offering a single configurable software and computing environment for multiple tenants. This contemporary multi-tenant service requires a multi-tenant database that accommodates data for multiple tenants using a single database schema. In general, traditional Relational Database Management Systems (RDBMS) do not support multi-tenancy and require schema extensions to provide multi-tenant capabilities. This paper proposes a multi-tenant database schema called Elastic Extension Tables (EET), which is highly flexible in enabling the creation of database schemas for multiple tenants by extending a preexisting business domain database, or by creating tenant business domain database from the scratch at runtime. The empirical results presented in this paper indicate that the EET schema has potential to be used for implementing multi-tenant databases for multi-tenant SaaS applications.**

***Index Terms*— Cloud Computing, Software as a Service, Multi-tenancy, Elastic Extension Tables, Multi-tenant Database.**

I. Introduction

CLOUD Computing has recently emerged as a new computing paradigm that transforms the IT industry, making the computing software and hardware more appealing to use as a service over the internet [17], [26]. This new computing paradigm has been gaining popularity for two reasons. First, the internet has become affordable and its speed has significantly increased [29]. Second, rapid growth in computer usage, in areas such as businesses, governments, health services, education, social media networks, mobile applications, and other computational aspects [17]. This increase in internet speed and the computer usage resulted in the need to maximize the use of computational resources and to minimize the cost. Cloud Computing offers a solution to this need by moving applications and their data from desktop and portable Personal Computers into large data centers [16]. Cloud Computing is rapidly evolving, with the prospects that it will be one day the fifth used utility after water, electricity, gasoline, and telephone [5], [15], [19]. Cloud Computing includes a number of service delivery models such as Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS) [16], [18], [24], [27]. Multi-tenancy is a fundamental characteristic of Cloud Computing services that allows SaaS vendors to run a single application that support multiple tenants using the same software and hardware infrastructure [13], [25], [28]. It is a common practice in SaaS applications to use a multi-tenant database architecture with a single database schema shared among all tenants [4], [21]. Cloud database service providers regard such a database as an effective resource sharing storage as it reduces the costs by co-locating multiple tenants' databases into a single database schema. It also reduces the total cost of ownership of the service. Such data architecture consists of two types of data: shared data and tenant's private isolated data. Combining these two types of data provides tenants with a complete view of data that fits their business requirements [7], [9].

Most modern Relational Database Management Systems (RDBMS) have been designed to manage data for a single tenant. However, single-tenant databases do not support the unique requirements of individual tenants and this can lead to incorrect assumptions and query plans [1], [21]. Various multi-tenant database schema techniques have been studied and implemented to overcome this challenge, including Private Tables, Extension Tables, Universal Table, Pivot Tables, Chunk Table, Chunk Folding, and XML Table [2], [8], [12], [14], [22], [21]. These multi-tenant schema techniques are based on traditional RDBMS [4], [7]. However, these multi-tenant schema techniques suffer from various limitations that still need to be addressed [5], [11], [21], [23], and overcoming these limitations in the context of SaaS applications has received a lot of attention, both from academic and industry-based researchers.

In this paper, we propose a novel multi-tenant database schema called Elastic Extension Tables (EET) that consists of Common Tenant Tables (CTT), Extension Tables (ET), and Virtual Extension Tables (VET). This multi-tenant schema enables tenants to build their own virtual database schema by creating the required number of tables and columns, creating virtual database relationships, and assigning suitable data types and constraints for table columns during multi-tenant application run-time execution. It also gives tenants the opportunity to address their individual business requirements by choosing from three database models: (1) Multi-tenant Relational Database, (2) Integrated Multi-tenant Relational Database with Virtual Relational Database, and (3) Virtual Relational Database. In addition, it allows tenants to store different data types, including structured, semi-structured, and unstructured data. In this paper, several experiments are performed to evaluate the feasibility and effectiveness of EET multi-tenant database schema by comparing it with Universal Table Schema Mapping (UTSM) [2], which is commercially used by Salesforce. Significant performance improvements obtained using EET when compared to UTSM, makes the EET schema a good candidate for implementing multi-tenant databases and multi-tenant applications.

The rest of the paper is organized as follows: section 2 discusses the related work of multi-tenant database schema designs. Section 3 proposes the Elastic Extension Tables multi-tenant database schema. Section 4 proposes three Elastic Extension Tables database models. Section 5 presents an example to compare other multi-tenant database schema designs with the Elastic Extension Table design. Section 6 presents a set of experiments that compare the performance of Elastic Extension Tables with Universal Table Schema Mapping. Section 7 concludes this paper and discusses future work.

II. Related Works

A number of multi-tenant database schema designs and techniques have studied and implemented to address multi-tenant database challenges. This section presents seven multi-tenant database schema techniques, including Private Tables, Extension Tables, Universal Table, Pivot Tables, Chunk Table, Chunk Folding, and XML Table [2], [8], [12], [14], [22], [23]. All of these multi-tenant database schema techniques are based on traditional RDBMS [4], [7].

A. Private Tables

The Private Tables technique allows each tenant to have his own private tables, which can be extended and changed [22], [23]. Using this multi-tenant query technique can be transformed from one tenant to another by renaming tables, and metadata without using extra columns like 'tenant_id' to distinguish and isolate the tenants' data. In contrast, many tables are required to satisfy each tenant needs. Therefore, this technique is suitable only for a small number of tenants to ensure sufficient database load and good performance [23].

B. Extension Tables

The Extension Tables are separated tables joined with the base tables by adding tenants' columns to construct logical source tables [22], [23]. This technique adapted from the Decomposed Storage Model that splitting up n-columns table into n 2-column tables joined using surrogate values [22]. Multiple tenants can use the base tables and the extension tables [7]. It is regarded as a better design when compared to Private Tables described above. Using this design, the number of tables grows with the number of tenants, and variety of their different business requirements [22].

C. Universal Table

A Universal Table contains a large number of columns that enable tenants to store their required columns. It is structured with two main columns 'tenant_id' and 'table_id', and other generic data columns, which have a flexible VARCHAR data type in which different data types with different data values can be stored in these columns [2], [22]. A flexible technique that enables tenants to extend their tables in different ways according to their business needs. However, the rows of the universal table can be too wide with an overhead in the number of NULL values, which the database has to handle [22].

D. Pivot Tables

In using the Pivot Tables technique, the application maps the schema into generic structure in the database, in which each column of each row in a logical source table is given its own row in the Pivot Table. The rows in the Pivot Table comprise of four columns, including tenant, table, column, and row that specifies which row in the logical source table they represent. It also includes a single data type column that stores the values of the logical source table rows according to their data types in the designated pivot Table [8], [21]. For example, the Pivot Tables can include two pivot tables, the first table 'pivot_int' to store INTEGER values, and the second table 'pivot_str' to store STRING values. The performance benefits are achieved using this technique by avoiding NULL values and by selectively reading from smaller numbers of columns. Pivot Tables technique, which partitions data vertically performs better when it allows selectively read in columns to improve the performance, when it compared with others multi-tenant database schema techniques that partition data horizontally (e.g. Universal Table) [22].

E. Chunk Table

The Chunk Table is another generic structure technique that is similar to Pivot Table, except it has a set of data columns with a mixture of data types that replace the column 'col' in the Pivot Table with 'chunk' column in the Chunk Table [22]. This technique partitions the logical source table into groups of columns. Each group is assigned a chunk ID and is mapped into an appropriate Chunk Table. This technique has four advantages over Pivot Table, including (1) Reducing metadata storage ratio, (2) reducing the overhead of reconstructing the logical source tables, (3) reducing the number of columns, and

(4) providing indexes. This technique is flexible, but it adds complexity to database queries [22].

F. *Chunk Folding*

Chunk Folding is a schema mapping technique that partitions logical source tables into chunks vertically [8], [22]. These chunks are folded in different physical tables and joined together, where a chunk of columns is partitioned into a group of columns and each group has a chunk id [8]. Aulbach et al. [22] performed experiments to measure the efficiency of Chunk Table and Chunk Folding techniques, and they found that Chunk Folding technique outperform the Chunk Table technique. In addition, they state that the performance of this technique is enhanced by mapping the most used tenants' columns of the logical schema into conventional tables, and the majority of tenants does not use the remaining columns in the Chunk Tables. However, the main limitation and weakness of the Chunk Folding technique is that the common schema that is used by multiple tenants must be known in advance, which is not a practical solution for multi-tenant databases. This issue is also present in Extension Tables, Pivot Tables, and Chunk Table multi-tenant schema techniques.

G. *XML Table*

The XML Table database extension technique is a combination of relational database and Extensible Markup Language (XML) [8], [12], [23]. The tenants' extension columns can be provided as native XML data type, or storing the XML document in the database as a Character Large Object (CLOB) or Binary Large Object (BLOB) [23]. XML data type facilitating the creation of database tables, columns, views, variables and parameters, and isolating the application from the relational data model [12]. This technique satisfies tenants' needs because their data can be handled without changing original database relational schema, and XML data type can be supported by several relational database products [8], [12]. However, this technique reduces the data access performance [23], and Heng et al. [14] state that this technique has the poorest performance (e.g. highest response time), when compared to Private Tables, Universal Table, Pivot Tables, Chunk Table and Chunk Folding techniques.

Heng et al. [14] conducted a number of experiments to evaluate retrieving data from five different multi-tenant schemas used in multi-tenant SasS applications, including Private Tables, Universal Table, Pivot Tables, Chunk Table, Chunk Folding, and XML Table. The results of these experiments show that retrieving data from Universal Table is faster than the other schema techniques, except the Private Tables schema. Aulbach et al. [23] conducted experiments to compare Private Table schema and the Universal Table (Spare Columns) schema. The results of these experiments show that the Universal Table schema has the same or better performance than the Private Tables schema when retrieving or inserting data, except when inserting a large amount of data, the Universal Table schema is slower than the Private Tables schema. Such experimental results lead to conclusion that the query performance of Universal Table schema is the best performance out of the five multi-tenant schema techniques, as the Private Tables schema is only suitable for a small number of tenants. Overall, the experimental results make the Universal Table schema the optimal schema to use for a multi-tenant database when it is compared to Pivot Tables, Chunk Table, Chunk Folding, and XML Table. Nevertheless, the Universal Table can be too large introducing overhead with the number of NULL values, which the database has to handle. This suggests that the currently available multi-tenant database schemas still have remaining challenges, and represent suboptimal designs. Section 5 presents an example that clarifies how the data is populated in the seven multi-tenant database schema designs that are discussed in this section.

III. Elastic Extension Tables

The EET multi-tenant database schema proposes a novel way of designing and creating an elastic database that consists of three table types, the first type is CTT, the second type is ET, and the third type is VET. Fig. 1 shows the details of EET multi-tenant schema. The design of this schema enables tenants to build their own virtual database schema by creating the required number of tables and columns, rows, creating virtual database relationships, and assigning suitable data types and constraints for table columns during the runtime execution of a multi-tenant application.

A. *Common Tenant Tables*

The Common Tenant Tables are the tables that can be shared between tenants who are using a multi-tenant single database schema. These tables are RDBMS, and are used as a business domain database schema that is shared between multiple tenants. For example, a multi-tenant application of a sales business domain may have a database schema with sales tables, such as salesperson, customer, product, sales-fact, and any other sales tables. These tables have columns that are used by most of the tenants, and the column tenant ID is used to differentiate between the tenants' rows. For example, the 'sales_person' CTT in Fig. 11 shows some common columns, such as 'first_name', and 'last_name', while the 'tenant_id' column is used to differentiate between the tenants' rows.

B. *Extension Tables*

The Extension Tables are metadata tables that are used to create virtual tables for multiple tenants who are using a single multi-tenant database schema during the application's runtime execution. They consists of the following eight physical tables:

1) *Db_table Extension Table*

The 'db_table' ET allows tenants to create virtual (logical) tables and give them unique names. The structure of this table has a composite primary key that consists of 'db_table_id' and 'tenant_id' columns. The 'db_table_id' column is a unique primary key of the table, while the 'tenant_id' column is a foreign key refers to the 'tenant' CTT and at the same time is a combined primary key with 'db_table_id' for this table. In addition, this table has the 'db_table_name' column that stores the virtual tables' names. In using this table, each tenant can have unique table names. For example, tenant-A can create a VET name 'sales_person', but cannot create the same VET name again for his VETs. However, tenant-B can create the 'sales_person' name even if tenant-A already created this VET's name.

2) *Table_column Extension Table*

The ‘table_column’ ET allows tenants to create virtual columns for a VET that created in the ‘db_table’ ET. The structure of this table has a composite primary key consists of ‘table_column_id’, ‘tenant_id’, and ‘db_table_id’. The ‘table_column_id’ is a unique primary key for this ET, while the other two columns ‘tenant_id’ and ‘db_table_id’ are primary keys in this table, and foreign keys that refer to primary key columns of the ‘tenant’ CTT, and the ‘db_table’ ET. Moreover, this table has other columns, including ‘table_column_name’, ‘default_value’, ‘data_type’, ‘is_indexed’, ‘is_null’, ‘is_relationship’, ‘is_primary_key_column’, and ‘is_unique_column’. The ‘table_column_name’ column has UNIQUE constraint, and VARCHAR data type. The ‘default_value’ column stores already defined value to be used once the database saves a table row, when there is no value specified to be stored in this column. The ‘data_type’ column specifies the data type of a virtual column that is stored into any of the three row ETs, which are presented in the following point. The ‘is_indexed’ column specifies whether a column has an index or not. The ‘is_null’ column specifies whether a column accepts to store NULL values or not, and if it does not, then this column is considered a mandatory column that must have a value. The ‘is_relationship’ column specifies whether a column has at least one relationship with any of the CTTs or the VETs. The ‘is_primary_key_column’ column specifies whether the column is a primary key. The ‘is_unique_column’ column specifies whether a column has a UNIQUE constraint.

3) *The Row Extension Tables*

The row ETs store virtual table rows for virtual extension columns in three separate ETs. Such ETs are separated in three tables in order to store small data values in the ‘table_row’ ET, which stores values such as NUMBER, DATE-and-TIME, BOOLEAN, VARCHAR and other data types. While large data values are stored in other two ETs, the first ET is the ‘table_row_blob’ that stores BLOB values of virtual columns that stores BLOB data type (e.g. Images, Audio, Video), and the second ET is the ‘table_row_clob’ that stores CLOB values for virtual columns that store TEXT data type (e.g. E-mails, web pages). The EET design separates these three ETs to reduce the impact of BLOB and CLOB values from slowing down virtual schema queries. These three tables have the same columns, except the table row ID column, which is called differently in the three tables. In the ‘table_row’ ET called ‘table_row_id’, in the ‘table_row_blob’ ET called ‘table_row_blob_id’, and in the ‘table_row_clob’ called ‘table_row_clob_id’. A table row ID can be given for several columns that map to one row in a VET. Fig.14 shows an example of this mapping. The corresponding columns in these three tables include, first, the ‘serial_id’ column which is a composite primary key in these tables. This column stores a serial number of a virtual column that maps to a row in the virtual table. Second, the foreign key columns, including ‘tenant_id’, ‘db_table_id’, and ‘table_column_id’ which at the same time are composite primary keys with the Table Row ID column and the ‘serial_id’ column. Third, the ‘value’ column that stores the virtual column values, however, the data types of these columns vary in each of the three row tables according to the data types that supposed to be stored in each table. These three row ETs are capable to store data types, including traditional relational data, texts, audios, images, videos, and XML in structured, unstructured, and semi-structured format. The structured data, such as traditional relational data can be stored in CTTs and VETs as it is presented in the EET design in Section 5. The un-structured data files such as images, audios, videos can be stored in EET, by storing the Uniform Resource Identifier (URI) of a file in the ‘table_row_blob’ ET. Then the actual physical file can be stored in a folder of a file system, and then this file can be accessed using the URI that stored in the ‘table_row_blob’ ET and mapped to the physical file that stored in a folder. The semi-structured data such as XML files can be used in two ways. Firstly, using the same method as used for storing unstructured data, then accessing the XML file using the URI that stored in the ‘table_row_blob’ ET and mapped to the physical XML file that stored in a folder. Secondly, an XML file can be stored as text in the ‘table_row_clob’ ET as a CLOB file, and then accessed from the ‘table_row_clob’ ET. It is being argued that RDBMSs are not scalable, because they are limited in offering good performance and scalability properties. Nevertheless, this issue can be resolved by using any of the available distributed software products in the market that scale and optimize RDBMSs on the cloud, such as MySQL Cluster, VoltDB, Clustrix, ScaleDB, NuoDB, ScaleBase [20], and many others.

4) *Primary Key Extension Table*

The ‘table_primary_key_column’ ET allows tenants to create virtual primary keys for the virtual extension columns which are stored in the ‘table_column’ ET. The structure of this table has a composite primary key consists of ‘table_primary_key_column_id’, ‘tenant_id’, ‘db_table_id’, and ‘table_column_id’. The ‘table_primary_key_column_id’ column is a unique primary key of the table, while the other three columns ‘tenant_id’, db_table_id’, and ‘table_column_id’ are primary keys and foreign keys. The ‘is_auto_increment’ column specifies whether a primary key can be auto-incremented or not. The ‘is_composite_key’ column is used to specify whether a virtual primary key that is stored in a table is a single primary key or a composite primary key.

5) *Relationship Extension Table*

The ‘table_relationship’ ET allows tenants to create virtual relationships between their VETs and CTTs. The table structure has a composite primary key consists of ‘table_relationship_id’, ‘tenant_id’, ‘db_table_id’, and ‘table_column_id’. The ‘table_relationship_id’ column is a unique primary key of the table, while the other three columns ‘tenant_id’, ‘db_table_id’, and ‘table_column_id’ are primary keys and foreign keys. The ‘table_type’ column specifies whether the relationship is with a CTT or a VET. The ‘target_table_id’ column is used to create a master-detail relationship between two VETs, by storing into it the table ID of the master VET that is stored in the ‘db_table’ ET, while the ‘targeted_column_id’ column is used to store into it the primary key ID of the master VET for the same relationship. The ‘shared_table_name’ column is used to create a master-detail relationship between a CTT and a VET, by storing into it the name of the master CTT while the name of the ‘shared_column_name’ column is used to store the primary key column name of the CTT for the same relationship. Furthermore, this ET can create a master-detail relationship between two VETs, or a CTT and a VET, even if the master table has composite primary keys. Such a relationship can be achieved by storing multiple table rows into the ‘table_relationship’ for the relationship that is between the master table that has a composite primary key, and the details VET. Each of these table rows denotes one of the primary key columns of the composite primary key that relates to the master table. The following are the database relationships that can be created using the ‘table_relationship’ ET between two VETs, two CTTs, or one VET and one CTT, including One-to-One, One-to-Many, Many-to-One, Many-to-Many, and Self-referencing.

6) *Index Extension Table*

The ‘table_index’ ET is used to add indexes for virtual columns of a VET to improve and speed up the query execution time when retrieve data from this VET. The structure of this table has a composite primary key consists of ‘table_row_id’, ‘serial_id’, ‘tenant_id’, ‘db_table_id’, and ‘table_column_id’. The column ‘table_row_id’ and ‘serial_id’ are unique primary keys that are referred to values stored into ‘table_row_id’ and ‘serial_id’ columns in the ‘table_row’ ET. While the other three columns ‘tenant_id’, ‘db_table_id’ and ‘table_column_id’ are primary keys and foreign keys for this table. The ‘value’ column stores a value that is stored in the ‘table_row’ ET and this value relates to an indexed virtual column, which is specified as an index in the ‘table_column’ ET by storing the necessary value in the ‘is_indexed’ column.

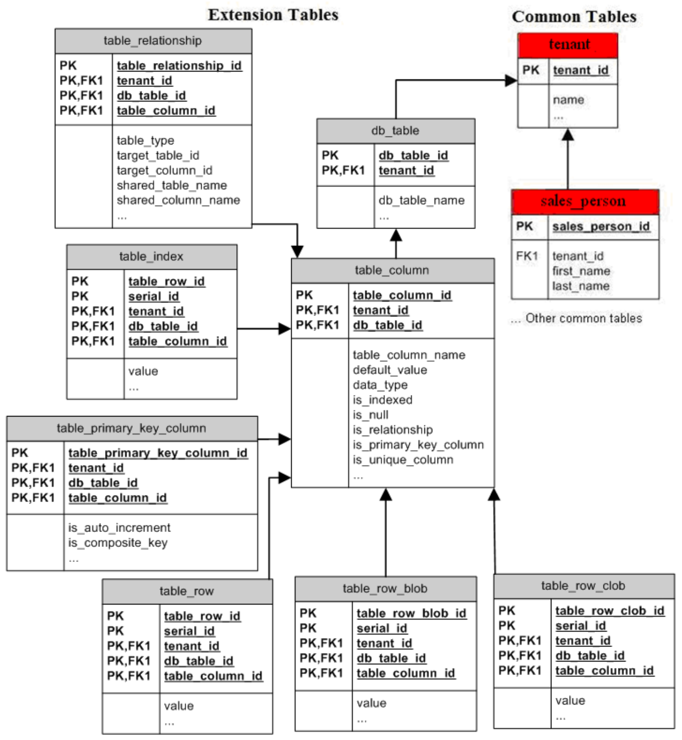


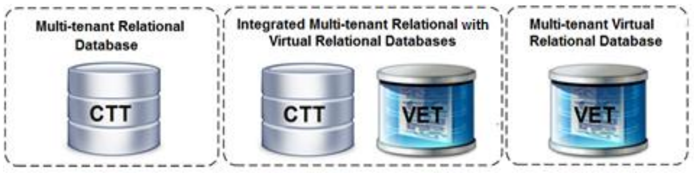
Fig. 1 Elastic Extension Tables.

C. *Virtual Extension Tables*

Virtual Extension Tables are the tables that tenants can create during the application’s runtime execution to extend an existing business domain database schema, or they can create their own virtual database schema from the scratch to fulfil their business needs. In Section 5, a detailed example is presented to explain how the tenants can create their VETs. In EET, VETs are created as a metadata into the eight ETs. In using this approach, the service provider who is offering a business domain database, can accommodate a large number of virtual tables by allowing tenants to populate these eight ETs with their data. This approach allows multi-tenant database service providers to manage their services in an efficient and cost-effective manner, and at the same time, it allows each tenant to configure its database schema according to its requirements.

IV. Elastic Extension Tables Database Models

The EET multi-tenant database schema allows the service provider to offer his tenants with the choice of using any of the following three database models (Fig. 2):



Multi-tenant Relational Database
CTT
Integrated Multi-tenant Relational with Virtual Relational Databases
CTT
VET
Multi-tenant Virtual Relational Database
VET

Fig. 2 EET Database Models.

A. *Multi-tenant relational database*

This database model allows tenants to use a standard relational database schema for a particular business domain database without the need to extend the existing database structures. This business domain database, can be shared between multiple tenants and differentiate between them by using a Tenant ID column in the CTTs (physical tables). This model can be applied to any business domain database such as Customer Relationship Management (CRM), Accounting, Human Resources (HR), or other business domains.

B. *Integrated multi-tenant relational database with virtual relational database*

This database model allows tenants to use a standard relational database schema for a particular business domain, extend it by adding additional virtual database tables, and combine these tables with the existing database structure by creating virtual relationships between them.

C. *Multi-tenant virtual relational database*

This database model allows tenants to create their virtual database schema from the scratch, by creating VETs, virtual database relationships between the VETs, and other database constraints to satisfy the tenants’ special business requirements of the tenants’ business domain applications.

For example, if a service provider offers a sales database schema to be used by multiple tenants, and with this database schema the service provider uses the EET, then this service provider can offer the three database models listed above that fulfil various business requirements. This example assumes that the service provider has three tenants.

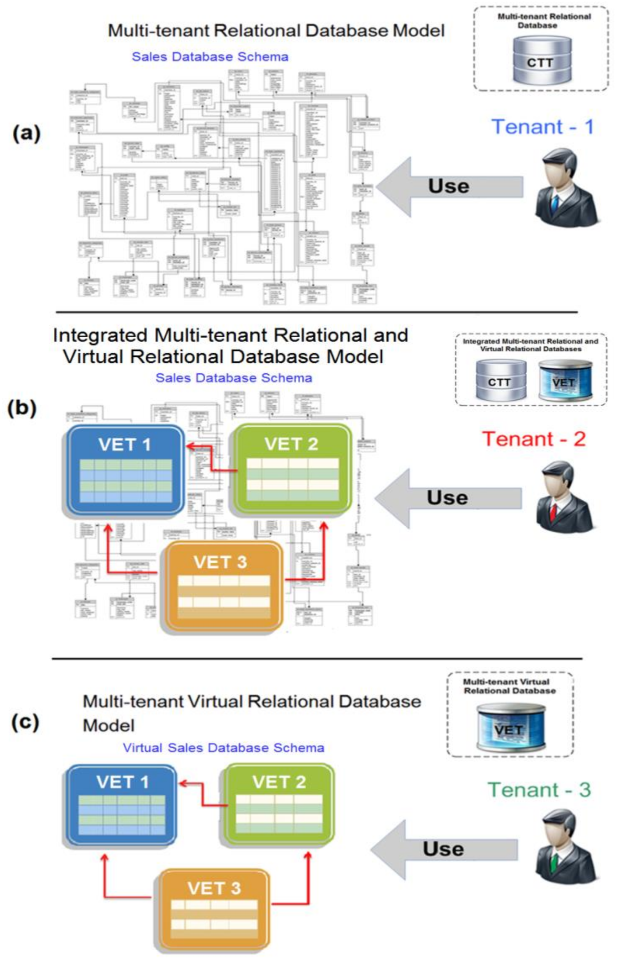

(a)
Multi-tenant Relational Database Model
Sales Database Schema
Multi-tenant Relational Database
CTT
Tenant - 1
Use
(b)
Integrated Multi-tenant Relational and Virtual Relational Database Model
Sales Database Schema
Integrated Multi-tenant Relational and Virtual Relational Databases
CTT
VET
VET 1
VET 2
VET 3
Tenant - 2
Use
(c)
Multi-tenant Virtual Relational Database Model
Virtual Sales Database Schema
Multi-tenant Virtual Relational Database
VET
VET 1
VET 2
VET 3
Tenant - 3
Use

Fig. 3 The EET Three Database Models Example.

The first user evaluated the Sales database, and found that this database suits his business requirements without any modifications. Therefore, this user will use the Sales database schema as originally provided by the service provider as illustrated in Fig. 3 (a). The second user has evaluated the Sales database schema and found that he needs to add extra tables to fulfil his business needs. Thus, this user created VET 1, VET 2, and VET 3, and then, created virtual database relationships between these VETs and the already existing physical tables (CTTs) in the sales database schema. The database model for this user is shown in Fig. 3 (b). The third user evaluated the same database schema and found that it did not suit his business requirements. Therefore, he decided not to use the Sales database schema at all, and instead created virtual relational tables from scratch and established database relationships between them as shown in Fig. 3 (c). This example illustrates the three database models of EET multi-tenant schema. These three database models allow tenants to design their databases and automatically configure their behaviors during their application's runtime execution.

V. An Example to Compare Multi-tenant Database Schema Designs With Elastic Extension Tables

This section presents an example that clarifies the seven multi-tenant database schema designs that presented in the related work section, and clarifies the differences between these designs and the EET multi-tenant schema design. This example shows three different tenants, including Tenant-A, Tenant-B, and Tenant-C. Each of these tenants uses a multi-tenant database, and in this database, they configure their sales database structure according to their different business needs. For simplicity, this example illustrates only one sales table that stores a sales person's information by using different multi-tenant database schema designs. Moreover, this example presents how the EET enables tenants to create their own database schema by extending an existing RDBMS database schema, including the required number of tables and columns, rows, virtual database relationships with any of the CTTs or VETs, primary keys for the columns, indexes for the columns, and assigning suitable data types for columns during multi-tenant application runtime execution. In order to show the difference between the table structures and how database is populated we use the same data across all the designs in this example.

The Private Tables in Fig. 4 show three tenants each of them with different Sales Person table that fulfil their business requirements. Tenant-A has the 'sales_person_tenant_a' table, which consists of six columns, including 'sales_person_id', 'first_name', 'last_name', 'phone', 'age', and 'gender'. Tenant-B has the 'sales_person_tenant_b' table, which consists of four columns, including 'sales_person_id', 'first_name', 'last_name', and 'business_id'. Tenant-C has the 'sales_person_tenant_c' table; the columns in this table are the same as 'sales_person_tenant_a' table. The same data that was used to populate the private table was used to populate the rest of the multi-tenant database schema designs and EET schema, which are presented in the example of this section.

sales_person_tenant_a

sales_person_id	first_name	last_name	phone	age	gender
100	Joseph	Richard	02123456789	25	male
101	Sarah	Smith	02123456788	34	female

Tenant-a (table 1)

sales_person_tenant_b

sales_person_id	first_name	last_name	business_id
200	David	John	123456

Tenant-b (table 2)

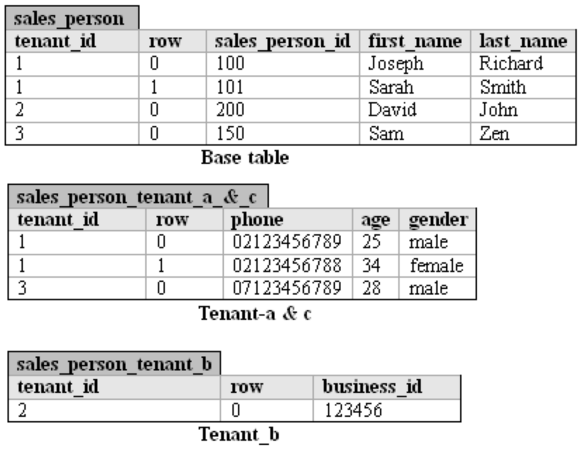
sales_person_tenant_c

sales_person_id	first_name	last_name	phone	age	gender
150	Sam	Zen	07123456789	28	male

Tenant-c (table 3)

Fig. 4 Private Tables.

The Extension Tables in Fig. 5 show how the columns of the Sales Person tables for the three tenants split-up between the base table 'sales_person' and two extension tables 'sales_person_tenant_a_&_c' and 'sales_person_tenant_b'. All of these three tables have two fixed common columns, including ‘tenant_id’ and ‘row’. The ‘tenant_id’ column is used to map data rows in the base table and the extension tables with the tenant who owns these rows. The ‘row’ column is used to give each row in the base table a row number and map it with other rows in the extension tables. The ‘sales_person’ base table has five columns, including ‘tenant_id’, ‘row’, ‘sales_person_id’, ‘first_name’, and ‘last_name’. All the tenants share the last three columns. The extension table ‘sales_person_tenant_a_&_c’ has five columns, including ‘tenant_id’, ‘row’, ‘phone’, ‘age’, and ‘gender’. This table is shared by two tenants Tenant-A and Tenant-C, due to the similarity in the extension columns that both tenants need. The ‘sales_person_tenant_b’ is used by Tenant-B, which has three columns ‘tenant_id’, ‘row’, and ‘business_id’.



sales_person

tenant_id	row	sales_person_id	first_name	last_name
1	0	100	Joseph	Richard
1	1	101	Sarah	Smith
2	0	200	David	John
3	0	150	Sam	Zen

Base table

sales_person_tenant_a_&_c

tenant_id	row	phone	age	gender
1	0	02123456789	25	male
1	1	02123456788	34	female
3	0	07123456789	28	male

Tenant-a & c

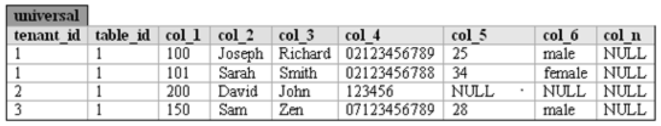
sales_person_tenant_b

tenant_id	row	business_id
2	0	123456

Tenant_b

Fig. 5 Extension Tables.

The Universal Table in Fig. 6 shows how the tenants’ data are stored in the universal table. This table has a number of columns, including ‘tenant_id’, ‘table_id’, and ‘col_1’ until ‘col_n’. The ‘tenant_id’ column is used to map rows with their tenants. The ‘table_id’ column is used to map rows to a particular table. The columns, including ‘col_1’ until ‘col_n’ are the universal columns that store any data the tenants wish to store to fulfil their business requirements.

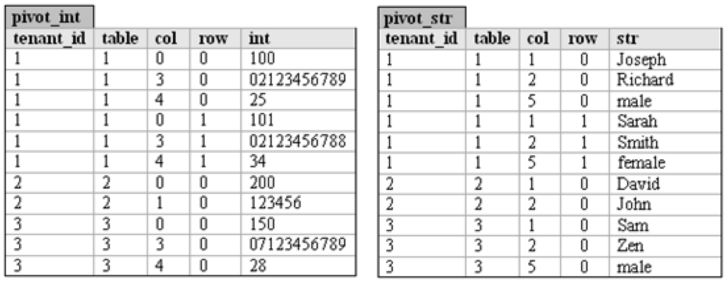


universal

tenant_id	table_id	col_1	col_2	col_3	col_4	col_5	col_6	col_n
1	1	100	Joseph	Richard	02123456789	25	male	NULL
1	1	101	Sarah	Smith	02123456788	34	female	NULL
2	1	200	David	John	123456	NULL	NULL	NULL
3	1	150	Sam	Zen	07123456789	28	male	NULL

Fig. 6 Universal Table.

The Pivot Tables in Fig. 7 show how the tenants’ data with a specific data type is stored in a specific pivot table. In this example, we have two pivot tables, the first table is ‘pivot_int’ that stores INTEGER data values, and the second table is ‘pivot_str’ that stores STRING data values. Each pivot table has standard columns, including ‘tenant_id’, ‘table’, ‘col’, and ‘row’. In addition to a column that can vary in each pivot table according to the data type that is specified for that table. For instance, the pivot table that stores STRING values will have a column that stores STRING values, and the column name could be called ‘str’. The ‘tenant_id’ column is used to map each row in a pivot table with a tenant. The ‘table’ column is used to map a data type value to a particular table. The ‘col’ column is used to map a data type value to a particular column in a particular table. The ‘row’ column is used to map a data type value to a particular row in a particular table.



pivot_int

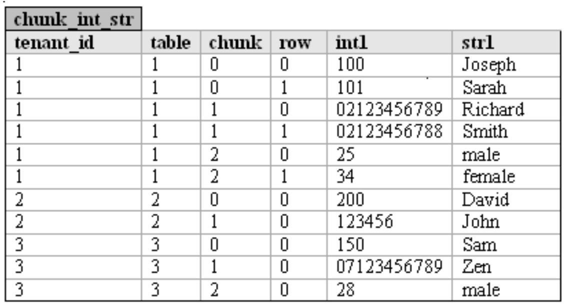
tenant_id	table	col	row	int
1	1	0	0	100
1	1	3	0	02123456789
1	1	4	0	25
1	1	0	1	101
1	1	3	1	02123456788
1	1	4	1	34
2	2	0	0	200
2	2	1	0	123456
3	3	0	0	150
3	3	3	0	07123456789
3	3	4	0	28

pivot_str

tenant_id	table	col	row	str
1	1	1	0	Joseph
1	1	2	0	Richard
1	1	5	0	male
1	1	1	1	Sarah
1	1	2	1	Smith
1	1	5	1	female
2	2	1	0	David
2	2	2	0	John
3	3	1	0	Sam
3	3	2	0	Zen
3	3	5	0	male

Fig. 7 Pivot Tables.

The Chunk Table in Fig. 8 shows how a set of data columns with a mixture of data types is structured. The ‘chunk_int_str’ table has six columns, including ‘tenant_id’, ‘table’, ‘chunk’, ‘row’, ‘int1’, and ‘str1’. The ‘tenant_id’ column is used to map each table row in a chunk table with a tenant. The ‘table’ column is used to map a table row to a particular table. The ‘chunk’ column is used to compound data for more than one logical column for a particular table. The ‘row’ column is used to map a data value to a particular row in a particular table. The ‘int1’ column is used to store all the INTEGER data values for different columns of different tables. The ‘str1’ column is used to store all the STRING data values for different columns of different tables.

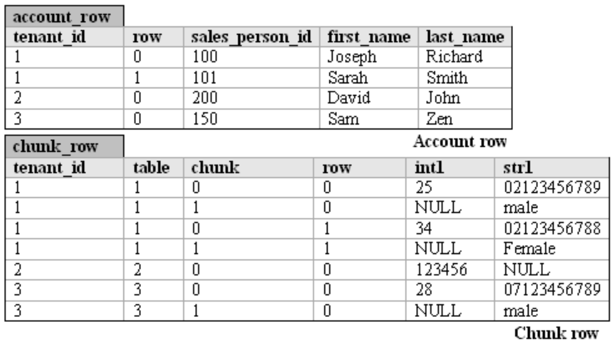


chunk_int_str

tenant_id	table	chunk	row	int1	str1
1	1	0	0	100	Joseph
1	1	0	1	101	Sarah
1	1	1	0	02123456789	Richard
1	1	1	1	02123456788	Smith
1	1	2	0	25	male
1	1	2	1	34	female
2	2	0	0	200	David
2	2	1	0	123456	John
3	3	0	0	150	Sam
3	3	1	0	07123456789	Zen
3	3	2	0	28	male

Fig. 8 Chunk Table.

The Chunk Folding tables in Fig. 9 show how the most commonly used tenants’ columns are structured in the ‘account_row’ table, while the remaining columns are structured into Chunk Folding table called ‘chunk_row’. The remaining columns that are used by tenants have extra business requirements, which are not applied in the common columns in the ‘account_row’ table. The ‘tenant_id’ column in both tables is used to map each table row with a tenant. The ‘row’ column in both tables is used to map a data value in a particular row of a particular table. The table ‘account_row’ consists of five columns, including ‘tenant_id’, ‘row’, ‘sales_person_id’, ‘first_name’, and ‘last_name’. The last three columns in this table are the common columns that are shared by the three tenants (Tenant-A, Tenant-B, and Tenant-C). The ‘chunk_row’ table consists of six columns, including ‘tenant_id’, ‘table’, ‘chunk’, ‘row’, ‘int1’, and ‘str1’. The ‘table’ column is used to map a row to a particular table. The ‘chunk’ column is used to combine data for more than one column for a particular table. The ‘int1’ column is used to store all the INTEGER data values for different columns of different tables. The ‘str1’ column is used to store all the STRING data values for different columns of different tables.



account_row

tenant_id	row	sales_person_id	first_name	last_name
1	0	100	Joseph	Richard
1	1	101	Sarah	Smith
2	0	200	David	John
3	0	150	Sam	Zen

Account row

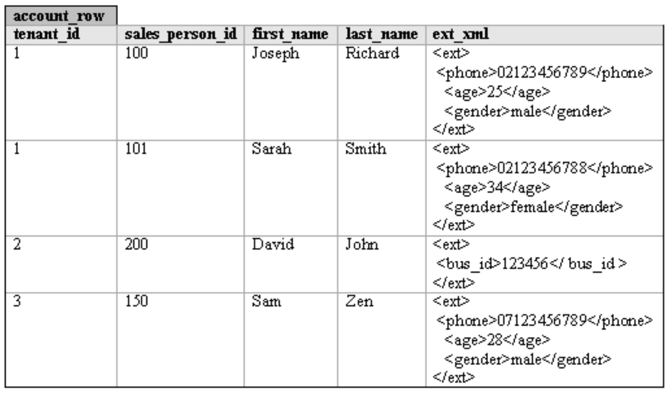
chunk_row

tenant_id	table	chunk	row	int1	str1
1	1	0	0	25	02123456789
1	1	1	0	NULL	male
1	1	0	1	34	02123456788
1	1	1	1	NULL	Female
2	2	0	0	123456	NULL
3	3	0	0	28	07123456789
3	3	1	0	NULL	male

Chunk row

Fig. 9 Chunk Folding.

The XML Table in Fig. 10 shows how this technique combines RDBMS and XML, by having fixed columns shared by all tenants, including ‘tenant_id’, ‘sales_person_id’, ‘first_name’, ‘last_name’. The ‘tenant_id’ column is used to map each table row in the ‘account_row’ table with a tenant. The rest of the columns are Sales Person columns that are shared by all tenants. The fifth column is ‘ext_xml’, this column is used to store an XML structure includes the rest of the logical columns that tenants may need to fulfil their extra business needs. For instance, as shown in the first table row in the ‘account_row’ table, there are three values stored using XML structure in the ‘ext_xml’ column, including phone, age, and gender.



account_row

tenant_id	sales_person_id	first_name	last_name	ext_xml
1	100	Joseph	Richard	<ext> <phone>02123456789</phone> <age>25</age> <gender>male</gender> </ext>
1	101	Sarah	Smith	<ext> <phone>02123456788</phone> <age>34</age> <gender>female</gender> </ext>
2	200	David	John	<ext> <bus_id>123456</ bus_id > </ext>
3	150	Sam	Zen	<ext> <phone>07123456789</phone> <age>28</age> <gender>male</gender> </ext>

Fig. 10 XML Table

Fig. 11 shows an example of the EET, which have three VETs that were created using the ETs. These three VETs are the tenants’ tables that presented in the Private Tables in Fig. 4. In this example, the ‘sales_person’ table is a CTT shared by all the three tenants and has predefined columns that are commonly used by these tenants. The Tenant-A has a business requirement to have a Sales Person table that includes the columns that predefined in the ‘sales_person’ CTT, in addition to three extra columns, including ‘phone’, ‘age’, and ‘gender’. This business requirement can be fulfilled by creating the ‘sales_person_tenant_a’ VET, and adding to this table these extra three columns. In addition to, adding the ‘sales_person_id’ column that is a virtual foreign key, which builds the virtual relationship between ‘sales_person_tenant_a’ VET and the ‘sales_person’ CTT. The Tenant-B has a business requirement to have a Sales Person table that includes the columns that are predefined in the ‘sales_person’ CTT, in addition to the ‘business_id’ column as an extra column to the CTT. This business requirement can be fulfilled for this tenant by creating the ‘sales_person_tenant_b’ VET, in addition, adding the ‘sales_person_id’ column that is a virtual foreign key, which builds the virtual relationship between ‘sales_person_tenant_b’ VET and the ‘sales_person’ CTT. The Tenant-C has a business requirement the same as the business requirement of Tenant-A. Therefore, the ‘sales_person_tenant_c’ VET of the Tennant-C has a similar structure and relationship of the ‘sales_person_tenant_a’ VET. The shared columns of the ‘sales_person’ CTT store the three tenants’ data, while the rest of the tenants’ data is stored in VETs by using the ETs, including ‘db_table’, ‘table_column’, ‘table_row’, ‘table_relationship’, table_index’, and ‘table_primary_key_column’. The details of this data are shown in Fig. 12 – 18.

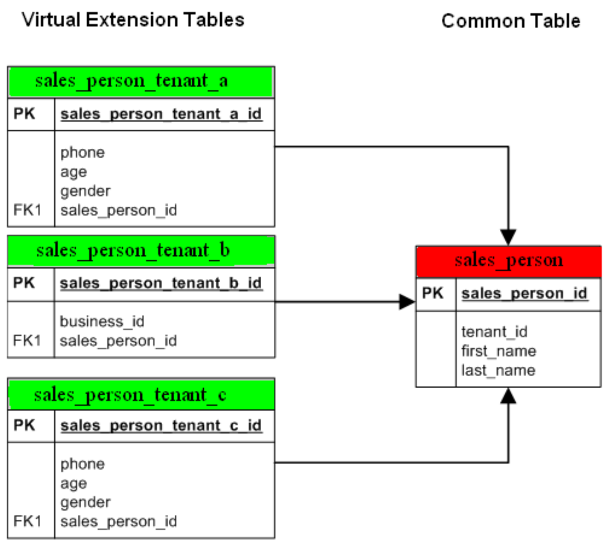
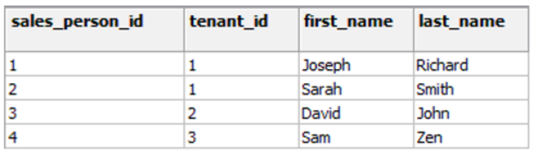
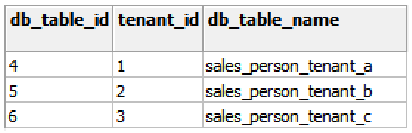


Fig. 11 Virtual Extension Tables (VET).



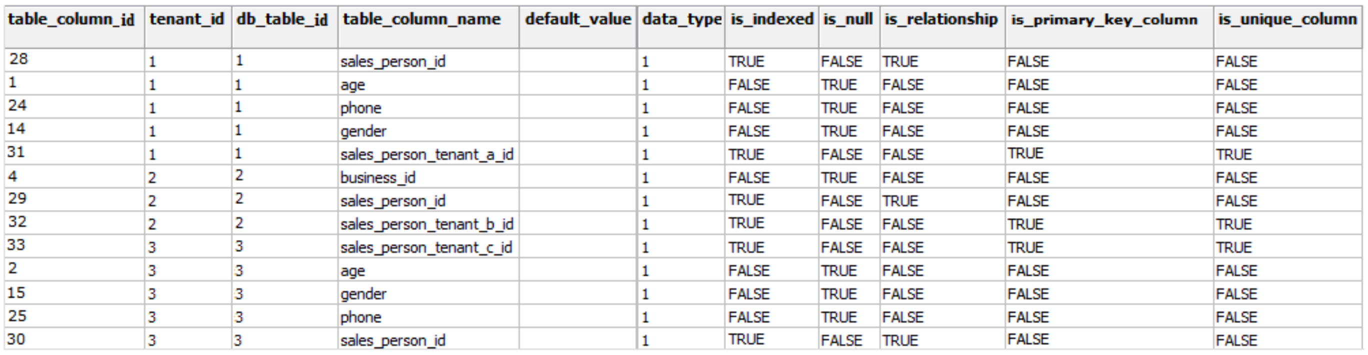
sales_person_id	tenant_id	first_name	last_name
1	1	Joseph	Richard
2	1	Sarah	Smith
3	2	David	John
4	3	Sam	Zen

Fig. 12 The data stored in the ‘sales_person’ CTT



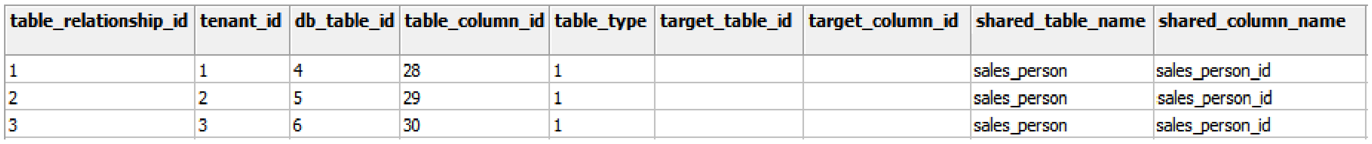
db_table_id	tenant_id	db_table_name
4	1	sales_person_tenant_a
5	2	sales_person_tenant_b
6	3	sales_person_tenant_c

Fig. 13 The data stored in the ‘db_table’ ET



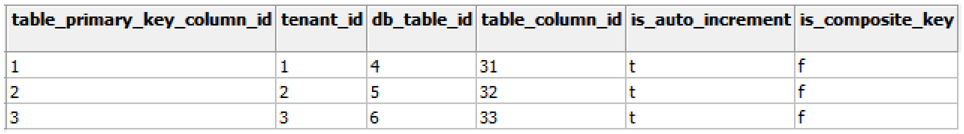
table_column_id	tenant_id	db_table_id	table_column_name	default_value	data_type	is_indexed	is_null	is_relationship	is_primary_key_column	is_unique_column
28	1	1	sales_person_id		1	TRUE	FALSE	TRUE	FALSE	FALSE
1	1	1	age		1	FALSE	TRUE	FALSE	FALSE	FALSE
24	1	1	phone		1	FALSE	TRUE	FALSE	FALSE	FALSE
14	1	1	gender		1	FALSE	TRUE	FALSE	FALSE	FALSE
31	1	1	sales_person_tenant_a_id		1	TRUE	FALSE	FALSE	TRUE	TRUE
4	2	2	business_id		1	FALSE	TRUE	FALSE	FALSE	FALSE
29	2	2	sales_person_id		1	TRUE	FALSE	TRUE	FALSE	FALSE
32	2	2	sales_person_tenant_b_id		1	TRUE	FALSE	FALSE	TRUE	TRUE
33	3	3	sales_person_tenant_c_id		1	TRUE	FALSE	FALSE	TRUE	TRUE
2	3	3	age		1	FALSE	TRUE	FALSE	FALSE	FALSE
15	3	3	gender		1	FALSE	TRUE	FALSE	FALSE	FALSE
25	3	3	phone		1	FALSE	TRUE	FALSE	FALSE	FALSE
30	3	3	sales_person_id		1	TRUE	FALSE	TRUE	FALSE	FALSE

Fig. 14 The data stored in the ‘table_column’ ET.



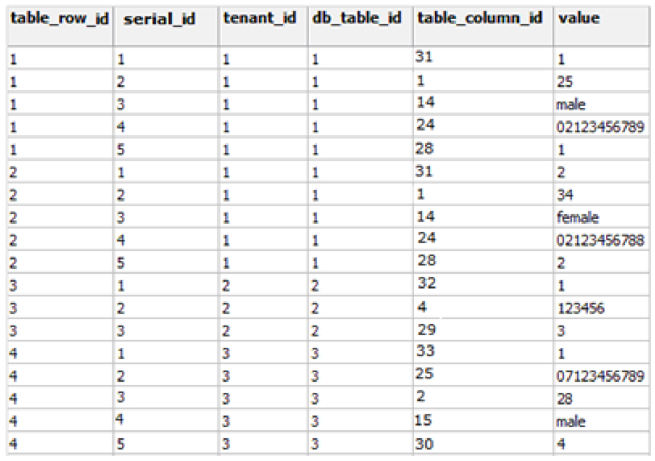
table_relationship_id	tenant_id	db_table_id	table_column_id	table_type	target_table_id	target_column_id	shared_table_name	shared_column_name
1	1	4	28	1			sales_person	sales_person_id
2	2	5	29	1			sales_person	sales_person_id
3	3	6	30	1			sales_person	sales_person_id

Fig. 15 The data stored in the ‘table_relationship’ ET.



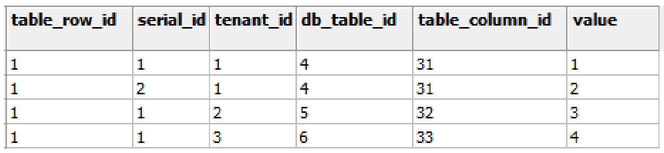
table_primary_key_column_id	tenant_id	db_table_id	table_column_id	is_auto_increment	is_composite_key
1	1	4	31	t	f
2	2	5	32	t	f
3	3	6	33	t	f

Fig. 16 The data stored in the ‘table_primary_key_column’ ET.



table_row_id	serial_id	tenant_id	db_table_id	table_column_id	value
1	1	1	1	31	1
1	2	1	1	1	25
1	3	1	1	14	male
1	4	1	1	24	02123456789
1	5	1	1	28	1
2	1	1	1	31	2
2	2	1	1	1	34
2	3	1	1	14	female
2	4	1	1	24	02123456788
2	5	1	1	28	2
3	1	2	2	32	1
3	2	2	2	4	123456
3	3	2	2	29	3
4	1	3	3	33	1
4	2	3	3	25	07123456789
4	3	3	3	2	28
4	4	3	3	15	male
4	5	3	3	30	4

Fig. 17 The data stored in the ‘table_row’ ET.



table_row_id	serial_id	tenant_id	db_table_id	table_column_id	value
1	1	1	4	31	1
1	2	1	4	31	2
1	1	2	5	32	3
1	1	3	6	33	4

Fig. 18 The data stored in the ‘table_index’ ET.

VI. Performance Evaluation

In this section, we compare the performance of accessing data from EET and Universal Table Schema Mapping (UTSM) [2]. In EET, data is partitioned vertically, when in UTSM data is partitioned horizontally. Liao et al. [2] state that the data architecture of UTSM is similar to Salesforce data architecture, which originated from the Universal Relations [6]. In addition, a number of database query examples presented in [2], [3], and used to retrieve data from this data architecture. Some of these queries are used in the experiments in this paper, in addition to other queries that are used to show the difference in accessing data from EET and UTSM. The UTSM technique had to be chosen to compare it with EET technique, because as discussed and concluded in the related work section, the Universal Table that is used in UTSM, is considered as the optimal schema design for multi-tenant applications. Moreover, this is one of the multi-tenant database schema techniques implemented commercially by Salesforce. The data architecture of UTSM is shown in Fig. 19. The ‘Data’ table is the universal table that stores all tenants’ data, and it has fixed number of data columns. The number of columns of this table should be large to accommodate the number of columns required by different tenants (e.g. Salesforce uses 500 columns for this table). These columns store data that maps to objects and fields created in the ‘Objects’ and ‘Fields’ tables. The data type of these columns is VARCHAR, which allows the storage of different data types (STRING, NUMBER, DATE, etc.). The ‘Objects’, ‘Fields’, and ‘Relationships’ tables are used to construct virtual tables and their virtual columns, and build relationships between these virtual tables. Whereas the ‘Index’ and ‘Uniquefields’ tables are used to optimize the query execution time of retrieving data from the ‘Data’ universal table [1], [2].

In this performance evaluation, the focus is on comparing the performance of accessing data from EET and UTSM directly from the database level, irrespective of the software solution built on top of these two multi-tenant database schemas for two reasons: (1) The most significant challenge in multi-tenant applications is designing multi-tenant database schema that improves multi-tenant query processing. This schema design influences the software design built on top of the schema and its performance. (2) Co mparing the performance of two multi-tenant software solutions under the same conditions, and using the same hardware resources is difficult, in particular as some software may not be available to be installed on the same application server.

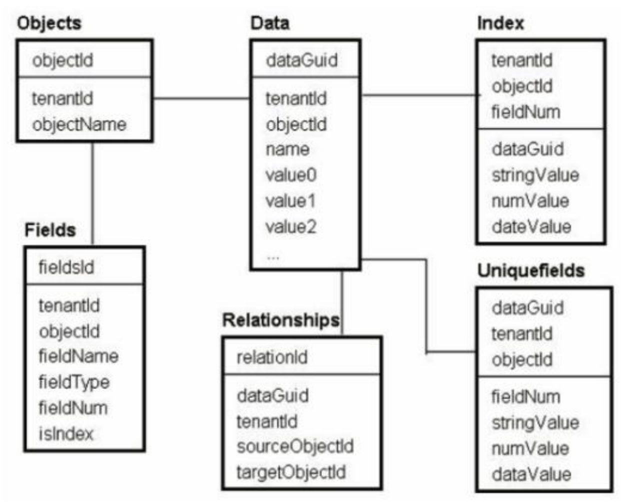


Fig. 19 Universal Table Schema Mapping [2].

A. Experimental Data Set and Setup

Typically, multi-tenant databases store massive data volumes across multiple servers to optimize the performance of data retrieval. However, before considering scale-up or scale-out for multi-tenant databases to optimize its performance, we believe that we should perform a comparison between EET and UTSM using a single server instance. In order to test the effectiveness of accessing data from these two multi-tenant database architecture designs without affecting their performance by using any scalability. In our experiments, we focus on benchmarking the performance of the main tables of both data architectures where most of the tenants' data is stored, and we disregard the lookup queries. For example, in EET, we discard the queries which check whether a virtual column is indexed or not from the 'table_column' ET. On the other hand, we disregard the queries which check whether a column is indexed or not from the 'fields' table of UTSM. In this case, our focus in EET is on 'table_row', and 'table_index' ETs, and in UTSM is on 'Data', 'Index', and 'Uniquefields' tables. Furthermore, in order to run comparative experiments, exactly the same data was populated in the 'table_row', and 'table_index' ETs of EET in a separate database, and the 'Data', 'Index', and 'Uniquefields' tables of UTSM in another database. No indexes were used other than the default indexes of each schema, which are the primary keys and the foreign keys indexes that are automatically generated in the RDBMS once the primary key and foreign key constraints are specified. The number of virtual rows that were already populated in 'table_row' ET is 200,000 rows and the same number of rows in the 'Data' universal table. These rows belong to the 'product' virtual table, and the structure of this table in EET and UTSM is shown in Fig. 20. There was no data populated in these two databases other than the populated 200,000 rows.

In the multi-tenant database, each tenant's data is isolated in a table partition. Therefore, the experiments are per-formed for one tenant to evaluate the effectiveness of retrieving data for each single tenant from the multi-tenant database. These experiments are divided into four types that are sharing the details of this data set. Each query of these experiments is performed ten times, and the average execution time of these queries is shown in Fig. 21 – 28. The queries that are related to EET and UTSM are shown in Table 1. The inputs and the outputs of EET and UTSM queries are the same. However, the structures of these queries are different because the data architectures of the two schemas are different. The four experiments details are listed below:

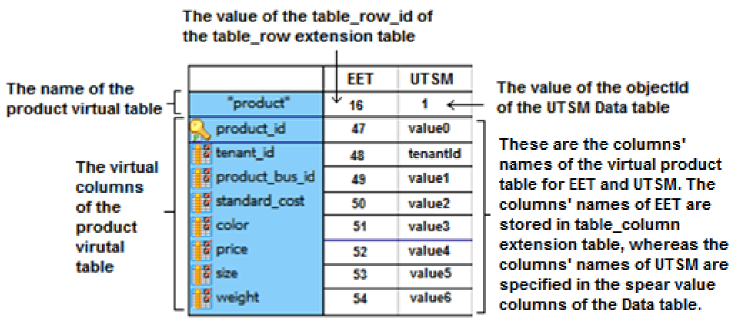

The value of the table_row_id of the table_row extension table
The name of the product virtual table
The value of the objectId of the UTSM Data table
The virtual columns of the product virutal table
These are the columns' names of the virtual product table for EET and UTSM. The columns' names of EET are stored in table_column extension table, whereas the columns' names of UTSM are specified in the spear value columns of the Data table.
EET
UTSM
"product"
16
1
product_id
47
value0
tenant_id
48
tenantId
product_bus_id
49
value1
standard_cost
50
value2
color
51
value3
price
52
value4
size
53
value5
weight
54
value6

Fig. 20. The virtual 'product' table structure.

1) Retrieving Rows Experiment (Exp.1)

The aim of this experiment is to benchmark the query execution time of retrieving rows from EET and UTSM. This experiment is divided into four experiments including:

Retrieving Rows without Using Query Columns Filters Experiment (Exp.1.1): In this experiment, Query 1 (Q1) and Query 2 (Q2) are executed. The Q1 retrieves rows from the 'table_row' ET of EET without specifying any query filters other than the tenant ID, and the 'project' table ID. Whereas the Q2 retrieves rows from the 'Data' universal table without specifying any query filters other than the tenant ID and the 'project' object ID. In this study, eight tests using these two queries are performed to retrieve 1, 10, 50, 100, 500, 1000, 1500, and 2000 rows.

Retrieving Rows Using Columns Query Filters Experiment (Exp.1.2): In this experiment, Query 3 (Q3) is executed on the 'table_row' ET of EET and Query 4 (Q4) is executed on the 'Data' universal table. Both queries are filtered by specifying particular numbers of product IDs stored in the 'product' virtual table. In this study, three tests using these two queries are performed to retrieve rows by specifying 1 product ID for the first test, 10 product IDs for the second test, and 50 product IDs for the third test. The structure of Q4 has presented in [3], but with different value settings.

Retrieving Rows Using Primary Key Indexes Experiment (Exp.1.3): In this experiment, Query 5 (Q5) is executed on the 'table_row' and 'table_index' ETs of EET and Query 6 (Q6) is executed on the 'Data' and 'Uniquefields' tables of UTSM. In this experiment, a primary key index is used to retrieve rows from the 'product' virtual table from the 'table_row' ET and from the 'Data' table. In this study, three tests using these two queries are performed to retrieve 1, 10, and 50 rows. The structure of Q6 has presented in [2], but with different value settings.

Retrieving Rows Using Custom Index Experiment (Exp.1.4): In this experiment, Query 7 (Q7) is executed on the 'table_row' and 'table_index' ETs of EET and Query 8 (Q8) is executed on the 'Data' and 'Index' tables of UTSM. In this experiment, a custom index is used, which is a selective filter in the tenant's query. This index should be other than the primary key and foreign key indexes. This custom index retrieves rows from the 'product' virtual table for both 'table_row' and 'Data' tables. The 'standard_cost' virtual column is chosen to filter the queries by looking up for all the products, which have a standard cost greater or equal '$ 9000' from the 'product' virtual table. In this study, four tests using these two queries are performed to retrieve 1, 10, 50, and 100 rows.

2) Inserting Rows Experiment (Exp.2)

The aim of this experiment is to benchmark the query execution time of inserting rows into EET and UTSM. Query 9 (Q9) is executed on the 'table_row' and 'table_index' ETs of EET and Query 10 (Q10) is executed on the 'Data', 'Index', and 'Uniquefields' tables of UTSM. In this study, four tests using these two queries are performed to insert 1, 10, 50, and 100 rows.

3) Updating Rows Experiment (Exp.3)

The aim of this experiment is to benchmark the query execution time of updating rows into EET and UTSM. Query 11 (Q11) is executed on the 'table_row' and 'table_index' ETs of EET and Query 12 (Q12) is executed on the 'Data', and 'Index' tables of UTSM. In this study, four tests using these two queries are performed to update 1, 10, 50, and 100 rows.

4) Deleting Rows Experiment (Exp.4)

Deleting Rows Experiment (Exp.4): The aim of this experiment is to benchmark the query execution time of deleting rows from EET and UTSM. Query 13 (Q13) is executed on the 'table_row' and 'table_index' ETs of EET, and Query 14 (Q14) is executed on the 'Data', 'Index', and 'Uniquefields' tables of UTSM. In this study, four tests using these two queries are performed to delete 1, 10, 50, and 100 rows.

The experiments were performed on PostgreSQL 8.4 database, using the default configuration setup. This database installed on a PC with 64-bit Windows 7 Home Premium operating system, Intel Core i5 2.40GHz CPU, 8 GB RAM memory, and 500 GB hard disk storage.

B. Experimental Result

This section gives four experimental results as follows:

1) Retrieving Rows

This experimental result was divided into four results as follows. The experimental study of Exp.1.1 shows that the execution time of Q1 that perform on the 'table_row' ET of EET is approximately 76% faster on average than the execution time of Q2 that perform on the 'Data' universal table when 1, 10, 50, 100, 500, 1000, 1500, and 2000 rows were retrieved. The details results of this experiment are shown in Fig. 21 – 22. The experimental study of Exp.1.2 shows that the execution time of Q3 that perform on the 'table_row' ET of EET is approximately 94% faster on average than the execution time of Q4 that perform on the 'Data' universal table when 1, 10, and 50 rows were retrieved. The details results of this experiment are shown in Fig. 23. The experimental study of Exp.1.3 shows

ABLE I
THE EXPERIMENTS QUERIES

Query No.	**Query Details**
Q1	SELECT * FROM table_row tr WHERE tr.table_row_id in (SELECT distinct(tr2.table_row_id) FROM table_row tr2 where tr2.db_table_id = 16 and tr2.tenant_id = 1000 **LIMIT 1**) ;
Q2	SELECT * FROM data WHERE tenantid = 1000 and objectId = 1 **LIMIT 1**;
Q3	SELECT * FROM table_row tr WHERE tr.tenant_id =1000 and tr.db_table_id = 16 and tr.table_column_id IN (50,52,54) and tr.table_row_id IN (SELECT table_row_id FROM table_row tr2 WHERE tr2.tenant_id =1000 and tr2.db_table_id = 16 and **(tr2.table_column_id =47 and tr2.value = '163336')**);
Q4 [3]	SELECT price, cost, weight FROM (SELECT value0 AS id, value4 AS price , value2 AS cost, value6 AS weight FROM data WHERE objectid = 1 and tenantid = 1000) AS product WHERE **id = '163336'**;
Q5	SELECT * FROM table_row tr WHERE tr.tenant_id =1000 and tr.db_table_id = 16 and tr.table_row_id IN (SELECT ti.table_row_id FROM table_index ti WHERE ti.tenant_id =1000 and ti.db_table_id = 16 and **ti.table_column_id =47 and ti.value = '163337'**)
Q6 [2]	SELECT * FROM data WHERE objectid =1 and tenantId = 1000 and dataguid in (SELECT dataguid FROM uniquefields WHERE objectid = 1 and tenantId = 1000 and **numvalue IN (163337)**);
Q7	SELECT * FROM table_row tr WHERE tr.tenant_id =1000 and tr.db_table_id = 16 and tr.table_row_id IN (SELECT ti.table_row_id FROM table_index ti WHERE ti.tenant_id = 1000 and ti.db_table_id = 16 and ti.table_column_id = 50 and **(cast (ti.value as numeric)** >= **'9000') LIMIT 1**);
Q8	SELECT * FROM data WHERE objectid =1 and tenantId = 1000 and dataguid in (SELECT dataguid FROM index WHERE objectid = 1 and tenantId = 1000 and fieldNum =3 and **numvalue > = 9000 LIMIT 1**);
Q9	INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,1,1000, '50000000',16,47); INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,2,1000, '1000',16,48); INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,3,1000, '50000',16,49); INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,4,1000, '222.50',16,50); INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,5,1000, 'Red',16,51); INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,6,1000, '242.50',16,52); INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,7,1000, '40',16,53); INSERT into table_row (table_row_id, serial_id, tenant_id, value, db_table_id, table_column_id) values (50000061,8,1000, '300',16,54); INSERT into table_index (tenant_id, value, table_row_id, serial_id, db_table_id, table_column_id) values (1000, '50000000',50000061,1,16,47); INSERT into table_index (tenant_id, value, table_row_id, serial_id, db_table_id, table_column_id) values (1000, '222.50',50000061,4,16,50);
Q10	INSERT into data (dataguid, tenantid, objectid ,name, value0, value1, value2, value3,value4, value5 ,value6) values(50000061,1000,1,'name', '50000000', '50000', '222.50','Red', '242.50', '40', '300'); INSERT into uniquefields values (50000061, 1000, 1, 1,'',50000000,'2013-12-12'); INSERT into index values (50000061, 1000, 1, 3,'', '222.50','2013-12-12');
Q11	UPDATE table_row set value = '230.50' WHERE tenant_id = 1000 and db_table_id = 16 and table_column_id = 52 and table_row_id =50000061; UPDATE table_index set value = '230.50' WHERE tenant_id = 1000 and db_table_id = 16 and table_column_id = 52 and table_row_id =50000061;
Q12	UPDATE data set value2 = '230.50' WHERE tenantid = 1000 and objectid = 1 and dataguid =50000061; UPDATE index set numvalue = 230.50 WHERE tenantid = 1000 and objectid = 1 and fieldnum =3 and dataguid =50000061;
Q13	DELETE from table_index WHERE tenant_id = 1000 and db_table_id = 16 and table_row_id =50000061; DELETE from table_row WHERE tenant_id = 1000 and db_table_id = 16 and table_row_id = 50000061;
Q14	DELETE from index WHERE tenantid = 1000 and objectid = 1 and fieldnum =3 and dataguid =50000061; DELETE from uniquefields WHERE tenantid = 1000 and objectid = 1 and fieldnum =1 and dataguid =50000061; DELETE from data WHERE tenantid = 1000 and objectid = 1 and dataguid =50000061;

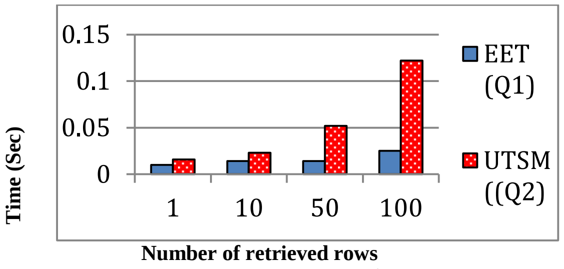


Fig. 21 Retrieving small numbers of rows (Exp. 1.1)

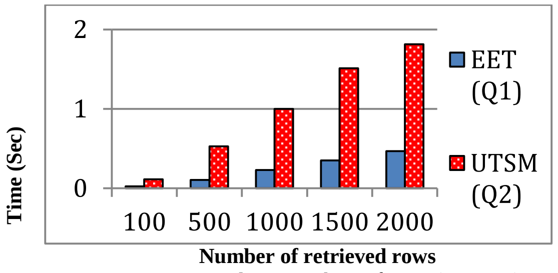


Fig. 22 Retrieving large numbers of rows (Exp. 1.1)

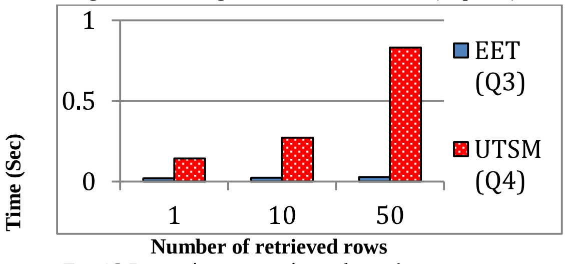


Fig. 23 Retrieving rows using columns' query filters (Exp.1.2)

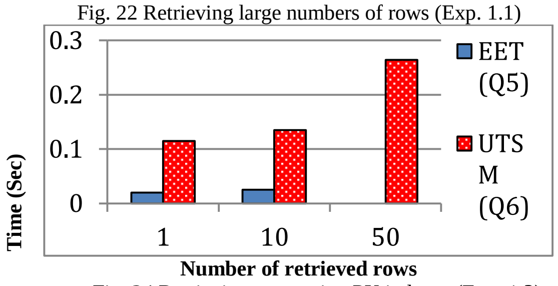


Fig. 24 Retrieving rows using PK indexes (Exp. 1.3)

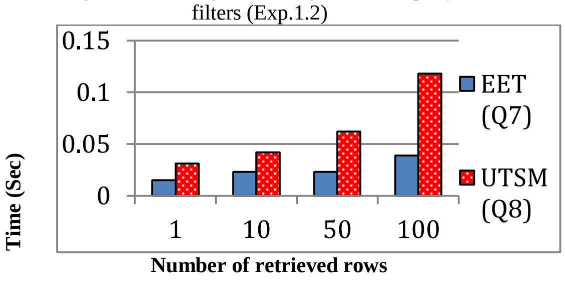


Fig. 25 Retrieving rows using custom indexes (Exp. 1.4)

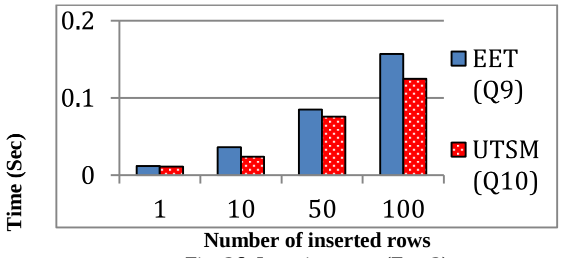


Fig. 26 Inserting rows (Exp.2)

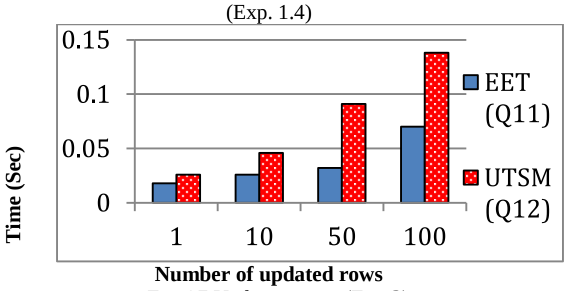


Fig. 27 Updating rows (Exp.3)

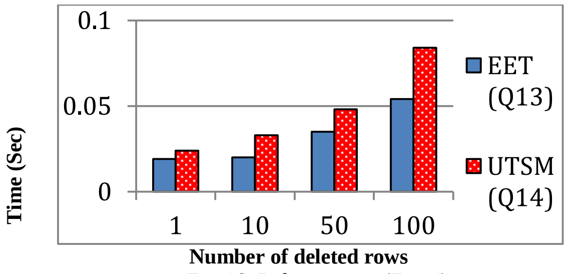


Fig. 28 Deleting rows (Exp.4)

that the execution time of Q5 that perform on the 'table_row' and 'table_index' ETs of EET is approximately 88% faster on average than the execution time of Q6 that perform on the 'Data' and 'Uniquefields' tables of UTSM when 1, 10, and 50 rows were retrieved. The details results of this experiment are shown in Fig. 24. The experimental study of Exp.1.4 shows that the execution time of Q7 that perform on the 'table_row' and 'table_index' ETs of EET is approximately 60% faster on average than the execution time of Q8 that perform on the 'Data' and 'Index' tables of UTSM when 1, 10, 50, and 100 rows were retrieved. The details results of this experiment are shown in Fig. 25.

2) Inserting Rows

The experimental study of Exp.2 shows that the execution time of Q9 that perform on the 'table_row' and 'table_index' ETs of EET is approximately 19% slower on average than the execution time of Q10 that perform on the 'Data', 'Index', and 'Uniquefields' tables of UTSM when 1, 10, 50, and 100 rows were inserted. The details results of this experiment are shown in Fig. 26.

3) Updating Rows

The experimental study of Exp.3 shows that the execution time of Q11 that perform on the 'table_row' and 'table_index' ETs of EET is approximately 51% faster on average than the execution time of Q12 that perform on the 'Data', and 'Index' tables of UTSM when 1, 10, 50, and 100 rows were updated. The details results of this experiment are shown in Fig. 27.

4) Deleting Rows

The experimental study of Exp.4 shows that the execution time of Q13 that perform on the 'table_row' and 'table_index' ETs of EET is approximately 32% faster on average than the execution time of Q14 that perform on the 'Data', 'Index', and 'Uniquefields' tables of UTSM when 1, 10, 50, and 100 rows were deleted. The details results of this experiment are shown in Fig. 28.

I. Conclusion and Future Work

In this paper, we propose a novel multi-tenant database schema design called EET, which consists of CTT, ET, and VET. EET allows tenants to create their own virtual database schema, including the required number of tables, columns, rows, virtual database relationships with CTTs or VETs, and assigns suitable data types and constraints for columns during the runtime of multi-tenant applications. EET is a single multi-tenant database schema that has a flexible way of creating database schemas for multiple tenants, by extending a business domain database based on RDBMS, or creating tenants business domain database from the scratch. EET design improves the multi-tenant database performance by avoiding NULL values, assigning primary keys to unique columns, providing indexes to table columns, and storing BLOB and CLOB data types in separate designated tables. In addition, EET design allows the storage of different data types, including structured, semi-structured, and unstructured data. In this paper, we only use structured data for the empirical evaluation, for two reasons. First, storing and retrieving data in XML files (semi-structured data) has the highest response time among the reviewed multi-tenant database schema designs [14], [23]. Thus, while semi-structured data can be stored in EET, it is not recommended as storage for multiple tenants. Second, there are many techniques for storing and retrieving different data types, and comparing all of these techniques with EET within the scope of a single paper is difficult due to the paper length limitations.

EET approach allows the creation of virtual relationships between the tenants' shared physical tables (CTT) and the tenants' virtual tables (VET), and allows tenants to choose from three database models: (1) Multi-tenant Relational Database, (2) Integrated Multi-tenant Relational Database with Virtual Relational Database, and (3) Virtual Relational Database. According to our knowledge, this capability is not included in any other multi-tenant database schema design.

We have compared and evaluated the performance of EET and UTSM. The design of EET partitions data vertically to avoid storing rows with NULL values. In contrast, the design of the Universal Table in UTSM partitions data horizontally, which can be associated with significant overheads as a result of a large number of NULL values. The experimental study reported in this paper shows an improvement when retrieving, updating and deleting data from EET over the UTSM. In particular, the experiments of retrieving data from EET indicate better performance when compared to UTSM. The execution time for inserting rows into EET is slightly longer than for inserting rows into UTSM. Overall, this experimental study makes the EET schema a good candidate for implementing multi-tenant databases and multi-tenant SaaS applications. As discussed in the related work section, the Universal Table used in UTSM is widely accepted as an optimal schema design for multi-tenant applications. Therefore, this study measured the feasibility and effectiveness of EET by comparing it with UTSM. Comparing EET with other existing multi-tenant database schema designs that are based on RDBMS and other data storage models will be considered in our future research. Furthermore, in our future research, we will evaluate the performance of EET using multiple tenants and focusing on the scalability of the EET approach.

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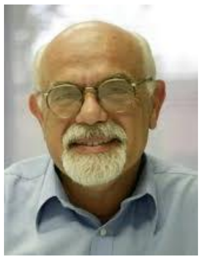
Haitham Yaish is an assistant professor at American University of the Middle East, and a member of Centre for Quantum Computation & Intelligent Systems at University of Technology, Sydney. Haitham received his PhD in information technology from University of Technology Sydney in 2014. He has 16 years industrial experience in the information technology field. His research interest is in Cloud Computing, Software as a Service, Big Data, and multi-tenancy.

Madhu Goyal is working as a Lecturer in the School of Software, University of Technology Sydney. She has done PhD in Computer Science (2002) from University of New South Wales, Australia. Her research is well recognized in the areas of agent-based computing, data mining and cloud computing. She has developed applications for the real-world systems or for domains such as Firefighting world, ecommerce, bioinformatics and intelligent tutoring systems. Her research in Cloud Computing is focused on how Software as Service providers can provide highly secured, optimized, configurable environment for same software and computing environment for multiple tenants.



George Feuerlicht is a senior lecturer at the University of Technology Sydney, and an Associate Professor at the Prague University of Economics, and Unicorn College. George is the author of over 100 publications across a range of topics in information systems and computer science, including recent publications on enterprise architectures, SOA, and Cloud Computing models. George is a member of ACM and a number of conference organizing and program committees. He holds a PhD from the Imperial College, London University, U.K.