

Spatio-temporal Queries in HBase

Xiaoying Chen¹ Chong Zhang² Bin Ge³ Weidong Xiao⁴
Science and Technology on Information Systems Engineering Laboratory
National University of Defense Technology
Changsha 410073, P.R.China

{¹chenxiaoying1991, ²leocheung8286}@yahoo.com ³gebin1978@gmail.com ⁴wilsonshaw@vip.sina.com

Abstract—Geoscience gives insights into our surroundings and benefits many aspects of our life. Nowadays, with massive sensors deployed to sense all kinds of parameters for environments, tens of billions, even trillions of sensed data are collected and need to be analyzed for surveillance or other purposes. From many perspectives, users always issue queries according to specific spatial and temporal predicates. For these applications, relational databases are overwhelmed by the large scale and high rate insertions, and NoSQL database could be considered a feasible solution. HBase, a popular key-value store system, is capable to solve the storage problem, but fails to provide in-built spatio-temporal querying capability.

Many previous works tackle the problem by designing schema, i.e., designing row key and column key formation for HBase, which we don't believe is an effective solution. In this paper, we address this problem from nature level of HBase, and propose an index structure as a built-in component for HBase. STEHIX (Spatio-TEmporal Hbase Index) is adapted to two-level architecture of HBase and suitable for HBase to process spatio-temporal queries. **It is composed of index in the meta table (the first level) and region index (the second level) for indexing inner structure of HBase regions.** Based on this structure, two common queries, range query and k NN query are solved by proposing algorithms, respectively. For achieving load balancing and scalable k NN query, two optimizations are also presented. We implement STEHIX and conduct experiments on real dataset, and the results show our design outperforms a previous work in many aspects.

Keywords—spatio-temporal query; HBase; range query; k NN query; load balancing

I. INTRODUCTION

With development of Geoscience, especially in Global Positioning System (GPS) and Remote Sensing (RS), the volume of spatio-temporal data accumulated to TB, even PB or EB. After storing spatio-temporal data, users always have requests of querying data by specific spatial and temporal predicate, which requires efficient storage and retrieval capability. Traditional database management systems (DBMSs) have advantage of data organization and are equipped with multi-dimensional index structures. However, dealing with large scale of data, they are incapable in high rate insertion and real time query. On the other hand, HBase [1], a key-value store system, can effectively support large scale data

operations, but do not natively support multi-attribute index, which limits the rich query applications.

A. Motivation

Our motivation is to adapt HBase to efficiently process spatio-temporal queries. Although some previous works proposed distributed index on HBase, but these works only consider spatial dimension, more critically, most of these works only concern how to design schema for spatial data, which do not tackle the problem from the nature level of HBase, except one, **MD-HBase [2] is designed to add index structure into the meta table, however, it doesn't provide index to efficiently retrieve the inner data of HBase regions.**

Our solution, STEHIX (Spatio-TEmporal Hbase Index), is built on two-level lookup mechanism, which is based on the retrieval mechanism of HBase. First, we use Hilbert curve to linearize geo-locations and store the converted one-dimensional data in the meta table, and for each region, we build a *region index* indexing the *StoreFiles* in HBase regions. We focus on range queries and k NN queries for such environment in this paper.

B. Contributions

We address how to efficiently answer range and k nearest neighbor (k NN) queries on spatio-temporal data in HBase. Our solution is called STEHIX (Spatio-TEmporal Hbase Index), which fully takes inner structure of HBase into consideration. The previous works focus on building index based on the traditional index, such as R-tree, B-tree, while our method constructs index based on HBase itself, thus, our index structure is more suitable for HBase retrieval. In other way, STEHIX considers not only spatial dimension, but also temporal one, which is more in line with user demand.

We use Hilbert curve to partition space as the initial resolution, the encoded value of which is used in the meta table to index HBase regions, then we use quad-tree to partition Hilbert cells as the finer resolution, based on this, we design *region index* structure for each region, which contains the finer encoded values for indexing spatial dimension and time segments for indexing temporal dimension. And later, we show such two-level index structure, meta table + *region index*, is more suitable for HBase to process

*This work is supported by NSF of China grant 61303062

query in the experiment. Based on our index structure, algorithms for range query and k NN query are devised, and load balancing policy and optimization to k NN query are also presented to raise STEHIX performance. We compare STEHIX with MD-HBase on real dataset, and the results show our design philosophies make STEHIX to be more excellent than the counterpart. In summary, we make the following contributions:

- We propose STEHIX structure which fully follow inner mechanism of HBase and is a new attempt on building index for spatio-temporal data in HBase platform.
- We propose efficient algorithms for processing range and k NN queries in HBase.
- We carry out comprehensive experiments to verify the efficiency and scalability of STEHIX.

The rest of this paper is organized as follows. Section 2 reviews related works. Section 3 formally defines the problem and prerequisites. Section 4 presents STEHIX structure. In section 5, algorithms for range and k NN queries are presented. Section 6 reports the optimizations to the index. And we experimentally evaluate STEHIX in section 7. Finally, section 8 concludes the paper with directions for future works.

II. RELATED WORKS

As an attractive alternative for large-scale data processing, Cloud storage system currently adopts a hash-like approach to retrieve data that only support simple keyword-based queries, but lacks various forms of information search. For data processing operations, several cloud data managements (CDMs), such as HBase, are developed. HBase, as NoSQL databases, is capable to handle large scale storage and high insertion rate, however, it does not offer much support for rich index functions. Many works focus on this point and propose various approaches.

Nishimura et al. [2] address multidimensional queries for PaaS by proposing MD-HBase. It uses k -d-trees and quad-trees to partition space and adopts Z-curve to convert multidimensional data to a single dimension, and supports multi-dimensional range and nearest neighbor queries, which leverages a multi-dimensional index structure layered over HBase. However, **MD-HBase builds index in the meta table, which does not index inner structure of regions, so that scan operations are carried out to find results, which reduces its efficiency.**

Hsu et al. [3] propose a novel Key formulation scheme based on R^+ -tree, called KR^+ -tree, and based on it, spatial query algorithm of k NN query and range query are designed. Moreover, the proposed key formulation schemes are implemented on HBase and Cassandra. With the experiment on real spatial data, it demonstrates that KR^+ -tree outperforms MD-HBase. KR^+ -tree is able to balance the number of false-positive and the number of sub-queries so that it improves the efficiency of range query and k NN query a lot. This

work designs the index according to the features found in experiments on HBase and Cassandra. However, it still does not consider the inner structure of HBase.

Zhou et al. [4] propose an efficient distributed multi-dimensional index (EDMI), which contains two layers: the global layer divides the space into many subspaces adopting k -d-tree, and in the local layer, each subspace is associated to a Z-order prefix R-tree (ZPR-tree). ZPR-tree can avoid the overlap of MBRs and obtain better query performance than other Packed R-trees and R^* -tree. This paper experimentally evaluates EDM I based on HBase for point, range and k NN query, which verifies its superiority. Compared with MD-HBase, EDM I uses ZPR-tree in the bottom layer, while MD-HBase employs scan operation, so that EDM I provides a better performance.

Han et al. [5] propose HGrid data model for HBase. HGrid data model is based on a hybrid index structure, combining a quad-tree and a regular grid as primary and secondary indices, supports efficient performance for range and k NN queries. This paper also formulates a set of guidelines on how to organize data for geo-spatial applications in HBase. This model does not outperform all its competitors in terms of query response time. However, it requires less space than the corresponding quad-tree and regular-grid indices.

HBaseSpatial, a scalable spatial data storage based on HBase, proposed by Zhang et al. [6]. Compared with MongoDB and MySQL, experimental results show it can effectively enhance the query efficiency of big spatial data and provide a good solution for storage. But this model does not compare with other distributed index method.

All the previous works we have mentioned above only consider the spatial query. For moving objects, a certain type of geo-spatial applications, requires high update rate and efficient real-time query on multi-attributes such as time-period and arbitrary spatial dimension. Du et al. [7] present hybrid index structure based on HBase, using R-tree for indexing space and applying Hilbert curve for traversing approaching space. It supports efficient multi-dimensional range queries and k NN queries, especially it is adept at skewing data compared with MD-HBase and KR^+ -tree. As this work focus on moving objects, it is different for our goal, and it also does not take the inner structure of HBase into account.

III. PROBLEM DEFINITION AND PREREQUISITES

In this section, we first formally describe spatio-temporal data, and then present the structure of HBase storage. For simplicity, only two-dimensional space is considered in this paper, however, our method can be directly extended into higher dimensional space.

A record r of spatio-temporal data can be denoted as $\langle x, y, t, \mathcal{A} \rangle$, where (x, y) means the geo-location of the record, t means the valid time when the data is produced, \mathcal{A} represents

other attributes, such as user-id, object's shape, descriptions, and etc.

We give the descriptions for structure of storage and index in HBase [8][9], for simplicity, some unrelated components, such as *HLog* and version, are omitted. Usually, an HBase cluster is composed of at least one administrative server, called *Master*, and several other servers holding data, called *RegionServers*.

Logically, a table in HBase is similar to a grid, where a cell can be located by the given row identifier and column identifier. Row identifiers are implemented by row keys (rk), and the column identifier is represented by column family (cf) + column qualifier (cq), where a column family consists of several column qualifiers. The value in a cell can be referred to as the format ($rk, cf:cq$). Table I shows a logical view of a table in HBase. For instance, value v_1 can be referred to as ($rk_1, cf_1:cq_1$).

Table I
LOGICAL VIEW FOR HBASE TABLE

	cf_1			cf_2	
	cq_1	cq_2	cq_3	cq_a	cq_b
rk_1	v_1	v_2	v_3	v_4	v_5
rk_2	v_6	v_7	v_8	v_9	v_{10}

Physically, a table in HBase is horizontally partitioned along rows into several regions, each of which is maintained by exactly one *RegionServer*. The client directly interacts with the respective *RegionServer* when executing read or write operations. When the data, formally as $\langle rk, cf:cq, value \rangle$ (we alternatively use term key-value data in rest of the paper), are written into a region, the *RegionServer* first keeps the data in a list-like memory structure called *MemStore*, where each entry is pre-configured with the same fixed size (usually 64KB) and the size of a certain number of entries is equal to that of the block of the underlying storage system, such as HDFS. When the size of *MemStore* exceeds a pre-configured number, the whole *MemStore* is written into the underlying system as a *StoreFile*, the structure of which is similar to that of *MemStore*. Further, when the number of *StoreFiles* exceeds a certain number, the *RegionServer* will execute the compaction operation to merge *StoreFiles* into a new large one. HBase provides a two-level lookup mechanism to locate the *value* corresponding to the key ($rk, cf:cq$). The catalog table *meta* stores the relation $\{[table\ name]:[start\ row\ key]:[region\ id]:[region\ server]\}$, thus given a row key, the corresponding *RegionServer* can be found, and then the *RegionServer* searches the *value* locally according to the given key ($rk, cf:cq$). Figure 1 shows an example of HBase two-level lookup structure.

From above descriptions, we can see that HBase only provides a simple hierarchical index structure based on the meta table, and the corresponding *RegionServer* must do scan work to refine the results, which would be inefficient

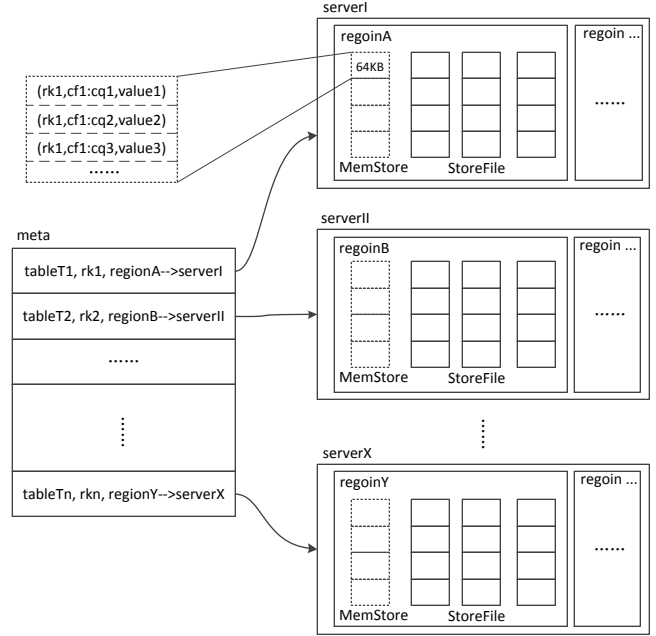


Figure 1. HBase Two-Level Lookup

to handle spatio-temporal queries.

IV. STEHIX STRUCTURE

In this section, we present the structure of our index, STEHIX (Spatio-TEmporal Hbase IndexX). The following philosophies are considered during index design, 1) for applications, it is not necessary for users to dedicatedly to design schema for query spatio-temporal data, i.e., our index should add no restriction on schema design, but a inner structure associated with HBase, 2) the index should be in accordance with the architecture of HBase as identical as possible, 3) the index should be adaptive to data distribution.

For design rule 1), we don't care the schema design and generalize each record to be a key-value data in *Store-File(MemStore)*, formally ($rk, cf:cq, r$), where $r = \langle x, y, t, A \rangle$.

For design rule 2), our index is built on the two-level lookup mechanism. In particular, we use Hilbert curve to linearize geo-locations and store the converted one-dimensional data in the meta table, and for each region, we build a *region index* to index the *StoreFiles*. Figure 2 shows an overview of STEHIX architecture.

A. Meta Table Organization

We use Hilbert curve to partition the whole space as the initial granularity. According to the design rationale of HBase, the prefix of row key should be different so that the overhead of inserting data could be distributed over *RegionServers*. And such design is able to satisfy this demand.

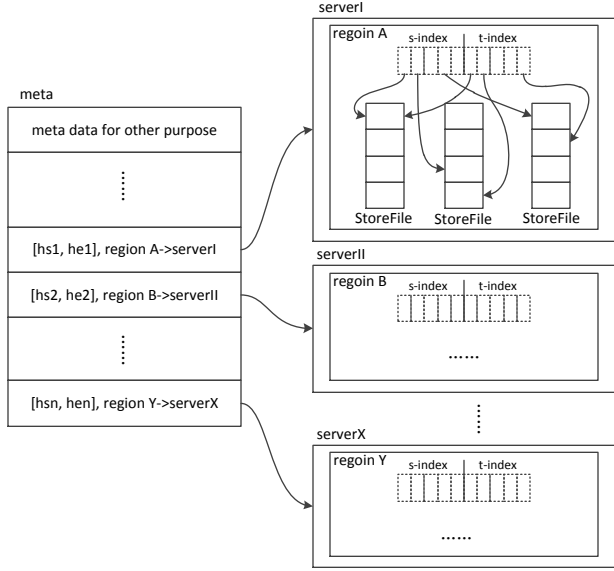


Figure 2. Overview of STEHIX

Hilbert curve is a kind of space filling curve which maps multi-dimensional space into one-dimensional space. In particular, the whole space is partitioned into equal-size cells and then a curve is passed through each cell for only once in term of some sequence, so that every cell is assigned a sequence number. Different space filling curves are distinguished by different sequencing methods. Due to information loss in the transformation, different space filling curves are evaluated by the criteria, locality preservation, meaning that how much the change of proximities is from original space to one-dimensional space. **Hilbert curve is proved to be the best locality preserved space filling curve [10].** With Hilbert curve, any object in the original space is transformed into $[0, 2^{2\lambda} - 1]$ space, where λ is called the order of Hilbert curve. Figure 3 shows four Hilbert curves in two-dimensional space with $\lambda=1, 2, 3$ and 4.

We describe three functions for Hilbert curve, first one is mapping a point in the original space to a value in one-dimensional space, the second is mapping a range window to a series of intervals, and the third is retrieving proximity cells of a point. Specifically, for a Hilbert curve with order= λ ,

- $coordToCell(p)$. Given a point $p=(x_1, x_2, \dots, x_n)$ in n -dimensional space \mathbb{S} , $coordToCell(p)$ returns a cell number (between 0 and $2^{2\lambda} - 1$) referring the cell where p lies within \mathbb{S} .
- $rectToIntervals(R)$. Given a range window $R=(x_1^l, x_2^l, \dots, x_n^l, x_1^u, x_2^u, \dots, x_n^u)$ in n -dimensional space \mathbb{S} , where x_i^l and x_i^u ($1 \leq i \leq n$) are the lower and upper bound of the i th-dimension, respectively, $rectToIntervals(R)$ returns a series of intervals representing the cells intersecting with R in \mathbb{S} .
- $getNeighborCells(p)$. Given a point $p=(x_1, x_2, \dots,$

$x_n)$ in n -dimensional space \mathbb{S} , $getNeighborCells(p)$ returns a list of cell numbers referring the cells which are neighbors of the cell $coordToCell(p)$.

For instance, in Figure 3 (b), $coordToCell(p_1) = 2$, $coordToCell(p_2) = 13$, $rectToIntervals(R_1) = \{[1,2], [7,8], [11,15]\}$, and $getNeighborCells(p_2)=\{1, 2, 7, 8, 11, 12, 15, 14\}$.

Based on above descriptions, we use Hilbert cell value as row key in the meta table to index spatio-temporal data as first level, thus, each record can be placed into the corresponding region according to Hilbert value of spatial part of the record. In particular, the following mapping structure is built in the meta table (for simplicity, table name is omitted): $\{[start\ Hilbert\ cell, end\ Hilbert\ cell]:[region\ id]:[region\ server]\}$. Initially, assuming there are N regions across M RegionServers, we can uniformly assign Hilbert cells to these regions, for instance, the first entry could be $\{[0, ((2^{2\lambda} - 1)/N) - 1] : regionA : serverI\}$, and the second $\{[(2^{2\lambda} - 1)/N, (2 * (2^{2\lambda} - 1)/N) - 1] : regionB : serverII\}$.

B. Region Index Structure

For retrieving local data efficiently, we design the *region index* which is kept in memory like *MemStore*. Considering *MemStore* is always kept in memory, *region index* is only to index *StoreFile*, however, for answering a query, *MemStore* must be scanned to guarantee the completeness of results.

Region index is a list-like in-memory structure, each entry of which points to a list of addresses referring to key-value data in the *StoreFile*. The *region index* consists of two parts, one is called *s-index* indexing spatial component of data, the other is called *t-index* indexing the temporal part, and such design is able to benefit query efficiency as we will see in next section.

For constructing *s-index*, the space is further partitioned at a finer granularity, i.e., each Hilbert cell is recursively divided by quad-tree and the resulting tiles are encoded with binary Z-Order. Such consideration is able to deal with the skewed data, i.e., when a hotspot is detected, quad-tree can be used recursively until the hotspot is eliminated. Later, we will use this idea to design an adaptive load balancing policy. After partitioning the Hilbert cell, each tile is corresponding to an entry in the *s-index*, i.e., the entry points to the key-value data whose geo-locations lie in that tile. For instance, Figure 4 shows an example of meta table and region index, where in the meta table, Hilbert cells $[0, 1]$ indexes *regionA : serverI* and $[2, 3]$ for *regionB : serverII*, respectively. For *regionA*, Hilbert cells 0 and 1 are divided using quad-tree into 11 tiles, 7 of which are 2-bit tiles and 4 are 4-bit tiles, and for each entry in *s-index*, the identifier is a combination of Hilbert value and binary Z-Order value, for instance, entry 0-10, where 0 is the number of Hilbert cell 0 and 10 is the code of lower-right tile in Hilbert cell 0, points

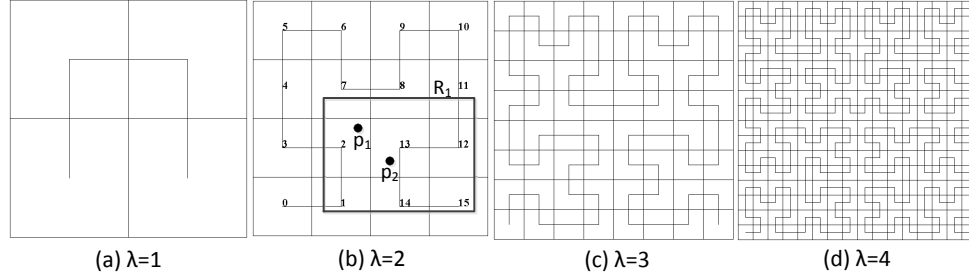


Figure 3. Hilbert Curves

to a list containing two addresses referring to two key-value records in *StoreFile*.

For building *t-index*, we use a period T to bound the length of the list of *t-index*, and such consideration is based on the fact that there may be some cycle for the spatial change of objects. The period T is divided into several segments, each of which is corresponding to an entry in *t-index*. Each entry points to a list of addresses referring to key-value data in *StoreFile*, whose temporal component modulo T lies in the segment. Continuing the example, Figure 4 shows the structure of *t-index*. Let $T=24$, which means a period of 24 hours is a cycle, and let each segment = 3 hours, which means T is divided into 8 segments, and entry [3, 6) points to 8 key-value data whose temporal value modulo 24 between 3 and 6.

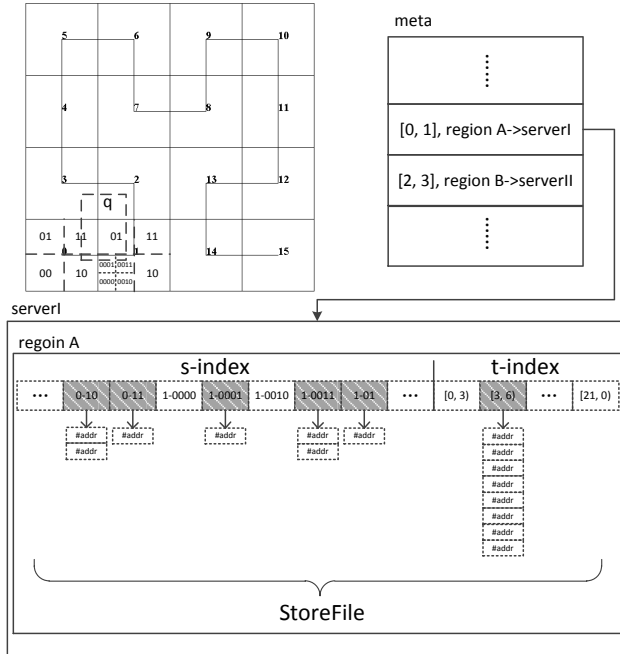


Figure 4. Region Index Structure

V. QUERY PROCESSING

In this section, the processing algorithms for range queries and k NN queries are presented.

A. Range Query

A range query $q=(x_l, y_l, x_u, y_u, t_s, t_e)$, aims to find all the records, whose geo-locations lie in the range (x_l, y_l, x_u, y_u) during time $[t_s, t_e]$.

The basic work flow for processing a range query q is described as follows, first, using Hilbert curve, spatial predicate (x_l, y_l, x_u, y_u) is converted into a set of one-dimensional intervals I_q , then according to mapping relation in the meta table, the involved *RegionServers* are informed to search the corresponding regions locally, utilized by *region index*. Here we propose a query optimization, i.e., using *s-index* and *t-index* to calculate selectivity, which is helpful to choose the high-selectivity to filter more unrelated data, in particular, the spatial predicate is recursively divided by quad-tree, the results of which are intersected with the entries in *s-index*, and then the number of addresses to key-value data can be calculated, say sn , similarly, using *t-index* can also calculate a number, tn , then if sn is less than tn , *s-index* is followed to retrieve results, other wise *t-index* is used.

Algorithm 1 describes the range query processing for STEHIX. In line 1, the spatial predicate is converted into one-dimensional intervals I_q , and the temporal predicate is converted into $[0, T]$ interval in line 2. In line 3, function *findRegions()* finds the involved regions which intersect with I_q . From line 4 to 11, each corresponding *region index* is inspected to retrieve results, in particular, *s-index* and *t-index* is used to calculate selectivity for the query, which is implemented by function *getCard()*, and the index with the lower cardinality is chosen to retrieve the results.

Figure 4 shows an example for range query processing in STEHIX. The spatial bound of q is depicted with dashed line and we assume that temporal predicate of q is [3, 6]. Then Hilbert cells 0 and 1 are intersected with q , thus, two entries in the meta table are examined, namely, $\{[0, 1] : \text{regionA} : \text{serverI}\}$ and $\{[2, 3] : \text{regionB} : \text{serverII}\}$. For instance, in *regionA*, the entries in *s-index* are intersected with spatial

Algorithm 1 Range Query Processing

Input: $q=(x_l, y_l, x_u, y_u, t_s, t_e)$ **Output:** $Qlist$ //result list

```
1:  $I_q = rectToIntervals(x_l, y_l, x_u, y_u)$ 
2:  $key_s = t_s \bmod T, key_e = t_e \bmod T$ 
3:  $Regions = findRegions(I_q)$ 
   /*the following processing is executed separately in each
   region*/
4: for each  $region \in Regions$  do
5:    $sn = region.s-index.getCard(x_l, y_l, x_u, y_u)$ 
6:    $tn = region.t-index.getCard(key_s, key_e)$ 
7:   if  $sn \leq tn$  then
8:      $Qlist \leftarrow region.s-index.seachIndex(q)$ 
9:   else
10:     $Qlist \leftarrow region.t-index.seachIndex(q)$ 
11:   end if
12: end for
13: return  $Qlist$ 
```

predicare of q , resulting 0-10, 0-11, 1-0001, 1-0011, 1-01 these 5 entries, which refer to totally 7 addresses to key-value data, and similarly, entry [3, 6) of $t-index$ refers to 8 addresses, consequently $s-index$ is followed to retrieve the results.

B. kNN Query

A kNN query could be formally defined as: given a set \mathcal{R} of spatio-temporal data records, a kNN query $q=(x_q, y_q, t_s, t_e, k)$, aims to find a set $\mathcal{R}(q) \subseteq \mathcal{R}$, such that $|\mathcal{R}(q)|=k$, and $d(o, (x_q, y_q)) \leq d(o', (x_q, y_q)), \forall o \in \mathcal{R}(q), o' \in \mathcal{R} \setminus \mathcal{R}(q)$, and $o.t, o'.t \in [t_s, t_e]$, where $d()$ is the Euclidean distance function.

We don't want to use n range queries to accomplish the kNN query, which means continuously enlarging spatial range of the query until k records are obtained [11], because we believe such a method would cause heavy querying overhead. We propose an approach utilized by incremental retrieval idea [12]. The basic work flow is, proximity objects of point (x_q, y_q) are constantly, incrementally retrieved until k results are found. In particular, first, Hilbert cell h containing point (x_q, y_q) is located, then the corresponding $region index$ is utilized to retrieve all records lie in h , meanwhile, neighbor cells of h are also retrieved, and these records and Hilbert cells are all enqueued into a priority queue where priority metric is the distance from (x_q, y_q) to record or Hilbert cell. Then top element is constantly dequeued and processed, either being added to result list or being followed to retrieve neighbor cells to be enqueued, until k results are found.

Algorithm 2 presents kNN query processing. The first line initializes a priority queue PQ where each element

is ordered by the distance from (x_q, y_q) to the element. The element can be Hilbert cell or record, and if it is a Hilbert cell, the distance is $MINDIST$ [13], other wise, the distance is the Euclidean distance from (x_q, y_q) to geo-location of the record. In line 2, the Hilbert cell containing (x_q, y_q) is gained, and is enqueued in line 3. From line 4, the procedure constantly retrieves top element e from PQ (line 5) and processes it, in particular, if e is a Hilbert cell (line 6), find the corresponding region rg from the meta table (line 7), and then the corresponding $region index$ is searched to retrieve all the records satisfying temporal predicate (line 8), which are enqueued into PQ (line 9 to 11), after that, the neighbor cells of e are obtained and enqueued into PQ (line 12 to 15); other wise, i.e., if e is a record (line 16), which means e is a result, e is added into $Qlist$ (line 17), and the above procedure is looped until the size of $Qlist$ reaches k (line 18 to 20).

Algorithm 2 kNN Query Processing

Input: $q=(x_q, y_q, t_s, t_e, k)$ **Output:** $Qlist$ //result list

```
1:  $PQ = null$  //initial a priority queue
2:  $h = coordToCell(x_q, y_q)$ 
3:  $PQ.enqueue(h, MINDIST((x_q, y_q), h))$ 
4: while  $PQ \neq \phi$  do
5:    $e = PQ.dequeue()$ 
6:   if  $e$  is type of cell then
7:      $rg = findRegions(e)$ 
8:      $RS = rg.findRecords(e, (t_s, t_e))$ 
9:     for each  $record \in RS$  do
10:       $PQ.enqueue(record, dist((x_q, y_q), record))$ 
11:   end for
12:    $CellSet = getNeighborCells(e.center)$ 
13:   for each  $cell \in CellSet$  do
14:      $PQ.enqueue(cell, MINDIST((x_q, y_q), cell))$ 
15:   end for
16:   else if  $e$  is type of record then
17:      $Qlist \leftarrow e$ 
18:     if  $Qlist.size()=k$  then
19:       return  $Qlist$ 
20:     end if
21:   end if
22: end while
```

VI. OPTIMIZATIONS

In this section, we propose two methods for raising performance of STEHIX from the aspects of load balancing and query optimization.

A. Adaptive Load Balancing

For achieving design rule 3), adaptive load balancing is considered. Our spatial partition procedure contains two phases, first is Hilbert curve, and the second is quad-tree. And load balancing is based on the second phase and region split, in particular, when the volume of a region exceeds a limit due to the hotspot in spatial dimension, the procedure detects which Hilbert cell is the hotspot, and uses a quad-tree to divide it into four subspaces, thus the original region is split into five regions, i.e., four corresponds to the four subspaces and one corresponds to the undivided Hilbert cell(s). After that, the meta table is also updated to renew the mapping information as well as the *region index*. Figure 5 shows an example of region split. We can see when a hotspot is generated in Hilbert cell 0, the cell is divided into four subspaces by quad-tree, and the corresponding region is split into five, namely, 0-00, 0-01, 0-10, 0-11 and 1, and the meta table and new regions are updated accordingly.

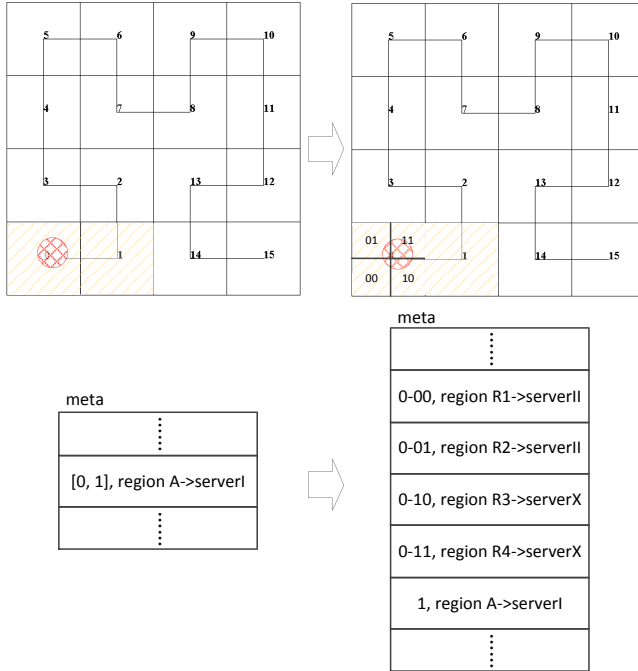


Figure 5. Load Balancing

B. Optimization for kNN Query

From kNN algorithm we can see, each time for retrieving the records of a Hilbert cell, the meta table must be searched to locate the corresponding region, which would increase overhead of the query. To deal with such a problem, we add modifications to *region index*, in particular, each *region index* ri is connected to the regions whose Hilbert cells are the neighbors of ri 's region's Hilbert cells. Thus, when *getNeighborCells()* method is invoked, the current region is able to retrieve records from proximity regions, however,

not all the records can be retrieved, and for this case, the meta table should be searched. Nevertheless, this optimization would reduce the overhead of querying the meta table.

VII. EXPERIMENTAL EVALUATION

We evaluate our algorithms on real dataset, which contains trajectories of taxis in Beijing¹. In particular, the dataset contains about 100 million records, and temporal range is from Nov. 1st to 3rd, and each record in the dataset contains vehicle ID, geo-location, recording time stamp, etc.

Our algorithms are implemented in Hadoop 2.5.1 and HBase 0.98.6, and run on a cluster with size varied from 5 to 33, in which each node is equipped with Intel(R) Core(TM) i3 CPU @ 3.40GHz, 4GB main memory (for *Master* 16GB), and 500GB storage, and operating system is CentOS release 6.5 64bit, and network bandwidth is 10Mbps. For comparison, we choose MD-HBase due to the similar function.

A. Range Queries

First, we evaluate the algorithm for range queries. And we introduce two parameters to test the algorithm under various conditions. One is selectivity θ defined as:

$$\theta = \frac{L(t_s, t_e)}{L_t} \cdot \frac{A_{R_q}}{A_S}$$

where $L(t_s, t_e)$ means the length of query temporal range (t_s, t_e) , L_t means the length of temporal extent of the dataset, A_{R_q} means the area of query spatial range R_q , and A_S means the area of the whole space. Selectivity specifies the size of the query range, and the larger θ is, the more spatio-temporal records are involved. In this experiment, the default values of θ and cluster size are 10% and 9, respectively. For each value of θ or size, we issue 10 queries with different temporal ranges and spatial ranges, and collect the average response time as the measurement of performance.

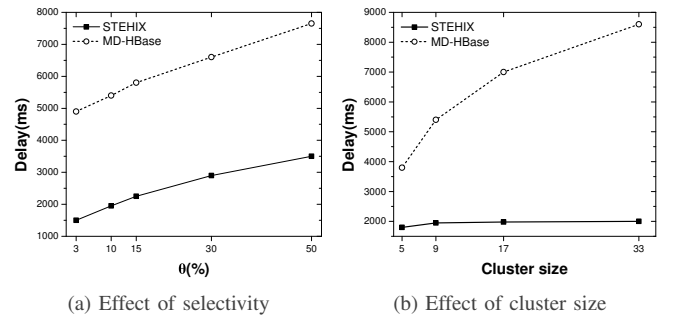


Figure 6. Experimental Results for Range Queries

First, we vary θ from 3% to 50% and Figure 6(a) shows the results. We can see that response time increases with

¹<http://activity.datatang.com/20130830/description>

θ for both methods. This is because a larger selectivity would access more records to be retrieved and examined, which increases the processing time. However, we can see STEHIX outperforms MD-HBase, which can be explained by the design of *region index*. Although MD-HBase builds index in the meta table, it doesn't index inner structure of regions, thus, scan operations are carried out to find results, which cost heavily. Our STEHIX is adapted to the two-level architecture of HBase, and is able to use *region index* to efficiently search each region, which highly improve performances.

Next, we vary cluster size from 5 to 33, and Figure 6(b) shows the results. It is apparent that STEHIX is excellent due to its nearly horizontal response time and good scalability. When the number of cluster size is increased, more *RegionServers* take part in the processing and use their *region indexes* parallel. However, due to lack of indexing *StoreFiles*, the scalability of MD-HBase is not good.

B. *k*NN Queries

In this experiment, the default values of k and cluster size are 8 and 9, respectively. First, we vary k from 4 to 32, and Figure 7(a) shows that STEHIX outperforms MD-HBase. When k is increased, both methods need more time to process queries. STEHIX uses less time to retrieve k results, which can be explained by the same reason, i.e., the *region index* embedded in HBase region. And then cluster size is varied from 5 to 33, still, STEHIX is better than MD-HBase, Figure 7(b) shows the fact.

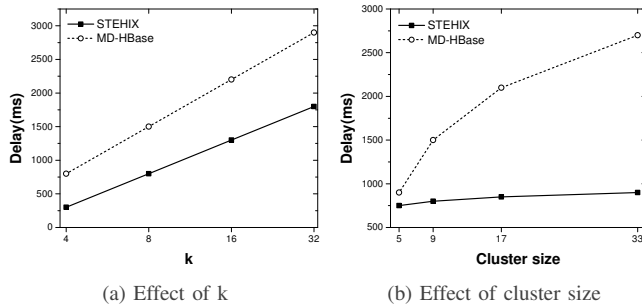


Figure 7. Experimental Results for k NN Queries

C. Effect of Optimizations

We examine the effect of optimizations to STEHIX in this experiment, and Figure 8 show the results. First, we use maximum imbalance load ratio [14] as metric, and test our adaptive load balancing policy, the results of comparison with non-load balancing are plotted in Figure 8 (a). We can see with cluster size increased, both ratios are raised, this is because the more nodes participate in the cluster, the more difficult is to distribute load uniformly, however, we can see our load balancing method indeed takes effect, i.e., when load balancing policy is used, the ratio is averagely around 6,

while the counterpart shows the performance about 38 to 70. Next, we test the effect of k NN optimization, from Figure 8 (b), we can see the connections among *region indexes* give chances to reduce querying overhead.

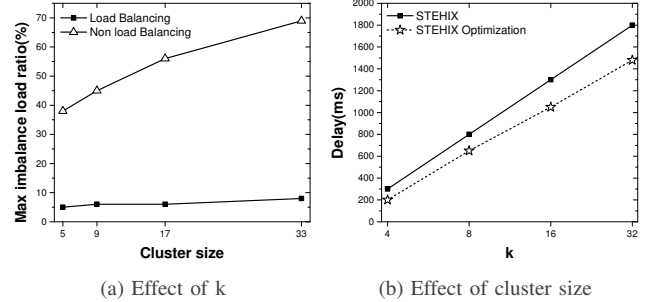


Figure 8. Experimental Results for Optimizations

VIII. CONCLUSION

With development of Geoscience, more and more spatio-temporal data need to be processed. To equip HBase with efficient and scalable spatio-temporal querying capability is a hot study field for big data area. Many previous works fail to tackle this problem due to lack of deep design for HBase. In this paper, we address the problem by proposing a novel index structure adapted to two-level architecture of HBase, which is suitable for HBase to process queries. Algorithms for range query and k NN query are designed, what's more, the optimizations for load balancing and k NN query are also proposed. We carry out extensive experimental studies for verifying our index, and the results show that our approach for HBase is more efficient and scalable than the previous work.

In the future, we plan to utilize this idea to efficiently store and retrieve graph data and apply to social networks.

ACKNOWLEDGMENT

This work is supported by NSF of China grant 61303062. We would like to thank Peijun He for helping with the implementation.

REFERENCES

- [1] H. Wiki, "Hbase: bigtable-like structured storage for hadoop hdfs."
- [2] S. Nishimura, S. Das, D. Agrawal, and A. E. Abbadi, "Md-hbase: a scalable multi-dimensional data infrastructure for location aware services," in *Mobile Data Management (MDM), 2011 12th IEEE International Conference on*, vol. 1. IEEE, 2011, pp. 7–16.
- [3] Y.-T. Hsu, Y.-C. Pan, L.-Y. Wei, W.-C. Peng, and W.-C. Lee, "Key formulation schemes for spatial index in cloud data managements," in *Mobile Data Management (MDM), 2012 IEEE 13th International Conference on*. IEEE, 2012, pp. 21–26.

- [4] X. Zhou, X. Zhang, Y. Wang, R. Li, and S. Wang, "Efficient distributed multi-dimensional index for big data management," in *Web-Age Information Management*. Springer, 2013, pp. 130–141.
- [5] D. Han and E. Stroulia, "Hgrid: A data model for large geospatial data sets in hbase," in *Cloud Computing (CLOUD), 2013 IEEE Sixth International Conference on*. IEEE, 2013, pp. 910–917.
- [6] N. Zhang, G. Zheng, H. Chen, J. Chen, and X. Chen, "Hbas-espacial: A scalable spatial data storage based on hbase," in *Trust, Security and Privacy in Computing and Communications (TrustCom), 2014 IEEE 13th International Conference on*. IEEE, 2014, pp. 644–651.
- [7] N. Du, J. Zhan, M. Zhao, D. Xiao, and Y. Xie, "Spatio-temporal data index model of moving objects on fixed networks using hbase," in *Computational Intelligence & Communication Technology (CICT), 2015 IEEE International Conference on*. IEEE, 2015, pp. 247–251.
- [8] A. HBase, "Apache hbase reference guide," Webpage available at <http://wiki.apache.org/hadoop/Hbase/HbaseArchitecture>. Webpage visited, pp. 04–04, 2012.
- [9] L. George, *HBase: the definitive guide*. "O'Reilly Media, Inc.", 2011.
- [10] C. Faloutsos and S. Roseman, "Fractals for secondary key retrieval," in *Proceedings of the eighth ACM SIGACT-SIGMOD-SIGART symposium on Principles of database systems*. ACM, 1989, pp. 247–252.
- [11] J. Wang, S. Wu, H. Gao, J. Li, and B. C. Ooi, "Indexing multi-dimensional data in a cloud system," in *Proceedings of the 2010 ACM SIGMOD International Conference on Management of data*. ACM, 2010, pp. 591–602.
- [12] G. R. Hjaltason and H. Samet, "Distance browsing in spatial databases," *ACM Transactions on Database Systems (TODS)*, vol. 24, no. 2, pp. 265–318, 1999.
- [13] N. Roussopoulos, S. Kelley, and F. Vincent, "Nearest neighbor queries," in *ACM sigmod record*, vol. 24, no. 2. ACM, 1995, pp. 71–79.
- [14] Q. H. Vu, B. C. Ooi, M. Rinard, and K.-L. Tan, "Histogram-based global load balancing in structured peer-to-peer systems," *Knowledge and Data Engineering, IEEE Transactions on*, vol. 21, no. 4, pp. 595–608, 2009.