Using space-filling curves for multi-dimensional indexing

Dr. Bisztray Dénes

Senior Research Engineer

In medias res

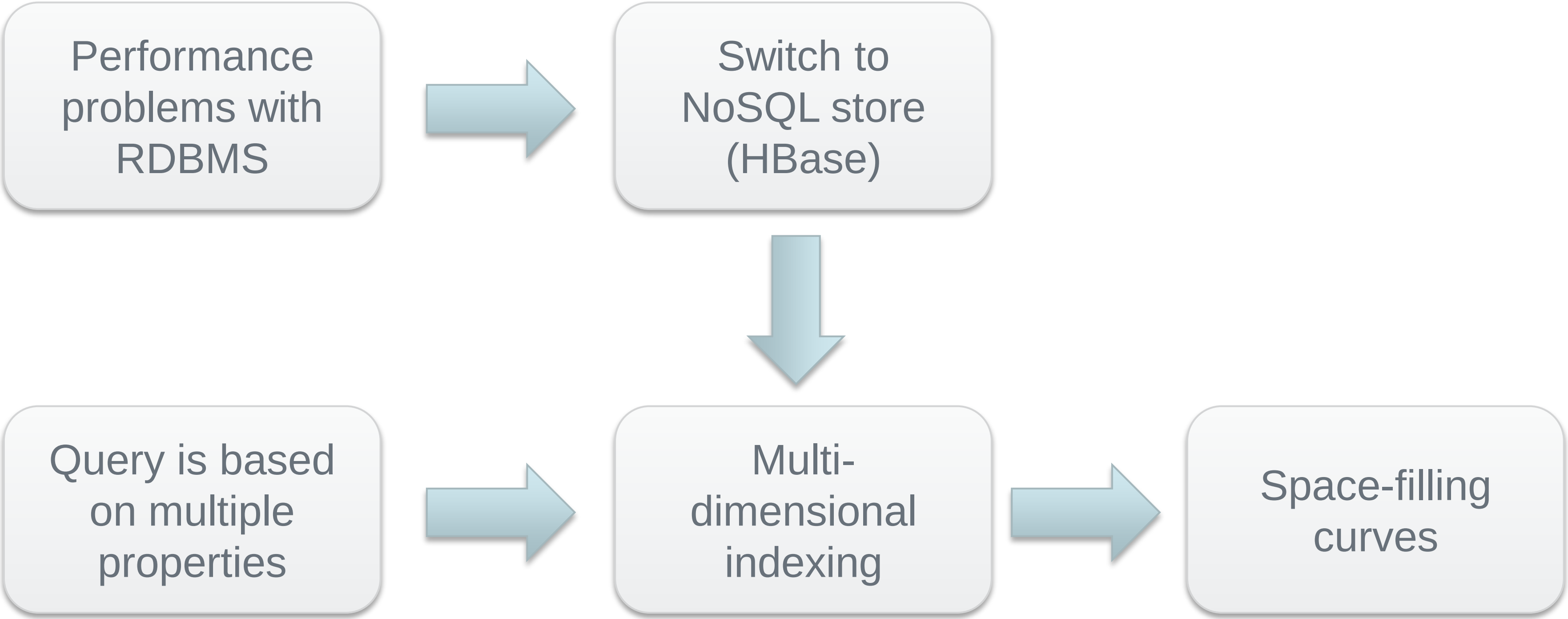


Table of Contents

- Brief introduction to indexes and databases
- The „main topic”, i.e. problem statement and ways to solve the problem
- Solution and Results

Databases and Indexes Introduction

Example of a Relation

attributes
(or columns)

ID	*name*	*dept_name*	*salary*
10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	60000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
58583	Califieri	History	62000
76543	Singh	Finance	80000
76766	Crick	Biology	72000
83821	Brandt	Comp. Sci.	92000
98345	Kim	Elec. Eng.	80000

tuples
(or rows)

Relation schema

- $A_1, A_2, \ldots, A_n$ are *attributes*

- $R = (A_1, A_2, \ldots, A_n)$ is a *relation schema*

  Example:

  instructor = (*ID*, *name*, *dept_name*, *salary*)

- Formally, given sets $D_1, D_2, \ldots. D_n$ a **relation *r*** is a subset of

  $D_1 \times D_2 \times \ldots \times D_n$

  Thus, a relation is a set of *n*-tuples $(a_1, a_2, \ldots, a_n)$ where each $a_i \in D_i$

- The current values (**relation instance**) of a relation are specified by a table

- An element ***t*** of ***r*** is a *tuple*, represented by a *row* in a table

NOKIA

Keys

- Let K $\subseteq$ R
- *K* is a **superkey** of *R* if values for *K* are sufficient to identify a unique tuple of each possible relation *r(R)*
  - Example: {*ID*} and {ID,name} are both superkeys of *instructor.*
- Superkey *K* is a **candidate key** if *K* is minimal
  Example: {*ID*} is a candidate key for *Instructor*
- One of the candidate keys is selected to be the **primary key**.
  - which one?

NOKIA

Indexing Basic Concepts

- Indexing mechanisms used to speed up access to desired data.
  - E.g., author catalog in library
- **Search Key** - attribute to set of attributes used to look up records in a file.
- An **index file** consists of records (called **index entries**) of the form

search key	pointer

- Index files are typically much smaller than the original file
- Two basic kinds of indices:
  - **Ordered indices:** search keys are stored in sorted order
  - **Hash indices:** search keys are distributed uniformly across "buckets" using a "hash function".

NOKIA

Ordered Indices

- In an **ordered index,** index entries are stored sorted on the search key value. E.g., author catalog in library.
- **Primary index:** in a sequentially ordered file, the index whose search key specifies the sequential order of the file.
  - Also called **clustering index**
  - The search key of a primary index is usually but not necessarily the primary key.
- **Secondary index**: an index whose search key specifies an order different from the sequential order of the file. Also called non-clustering index**.**
- Index-sequential file**:** ordered sequential file with a primary index.

NOKIA

Dense Index Files

- **Dense index** — Index record appears for every search-key value in the file.
- E.g. index on *ID* attribute of *instructor* relation

10101	
12121	
15151	
22222	
32343	
33456	
45565	
58583	
76543	
76766	
83821	
98345	

10101	Srinivasan	Comp. Sci.	65000	
12121	Wu	Finance	90000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
32343	El Said	History	60000	
33456	Gold	Physics	87000	
45565	Katz	Comp. Sci.	75000	
58583	Califieri	History	62000	
76543	Singh	Finance	80000	
76766	Crick	Biology	72000	
83821	Brandt	Comp. Sci.	92000	
98345	Kim	Elec. Eng.	80000	

Sparse Index Files

- **Sparse Index**: contains index records for only some search-key values.
  - Applicable when records are sequentially ordered on search-key
- To locate a record with search-key value *K* we:
  - Find index record with largest search-key value < *K*
  - Search file sequentially starting at the record to which the index record points

10101	
32343	
76766	

10101	Srinivasan	Comp. Sci.	65000	
12121	Wu	Finance	90000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
32343	El Said	History	60000	
33456	Gold	Physics	87000	
45565	Katz	Comp. Sci.	75000	
58583	Califieri	History	62000	
76543	Singh	Finance	80000	
76766	Crick	Biology	72000	
83821	Brandt	Comp. Sci.	92000	
98345	Kim	Elec. Eng.	80000	

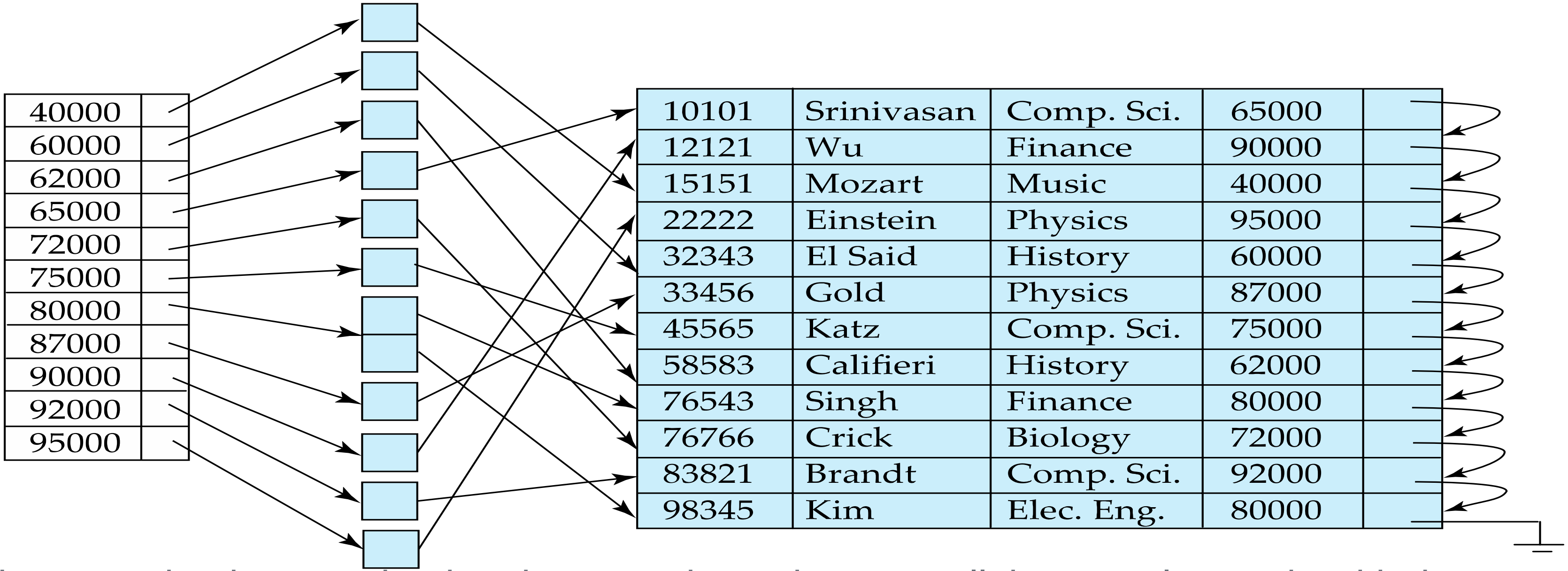
NOKIA

Secondary Indices

- Frequently, one wants to find all the records whose values in a certain field (which is not the search-key of the primary index) satisfy some condition.
  - Example 1: In the *instructor* relation stored sequentially by ID, we may want to find all instructors in a particular department
  - Example 2: as above, but where we want to find all instructors with a specified salary or with salary in a specified range of values
- We can have a secondary index with an index record for each search-key value

Secondary Indices Example

Secondary index on *salary* field of *instructor*



- Index record points to a bucket that contains pointers to all the actual records with that particular search-key value.
- Secondary indices have to be dense

Multi dimensional indexing and the space filling curves

Application Characteristics

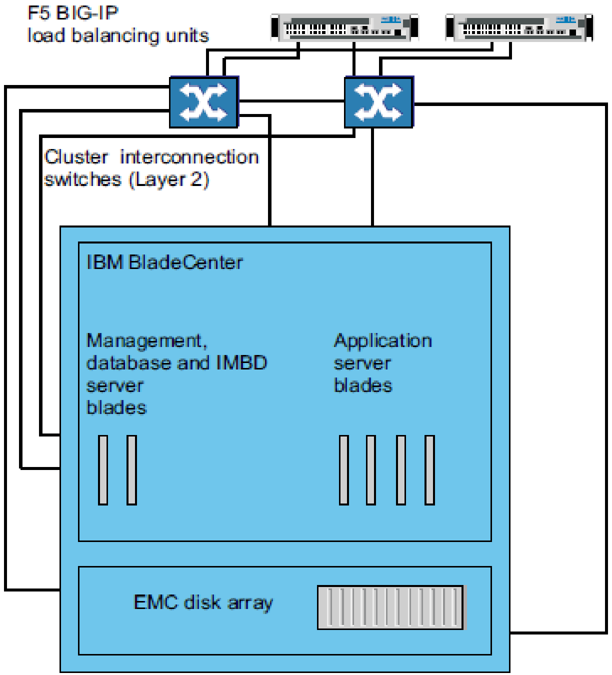
- Statistic analysis of massive CDR data to generate Business Reports:
  - On-demand report with URL **and** Time Range
  - On-demand report with MSISDN **and** Time Range
- Data-intensive and performance-critical application:
  - Cut down the reporting response time from hours to minutes
  - Extremely high load to Disk I/O due to high throughput requirement

Technical Requirements for Storage

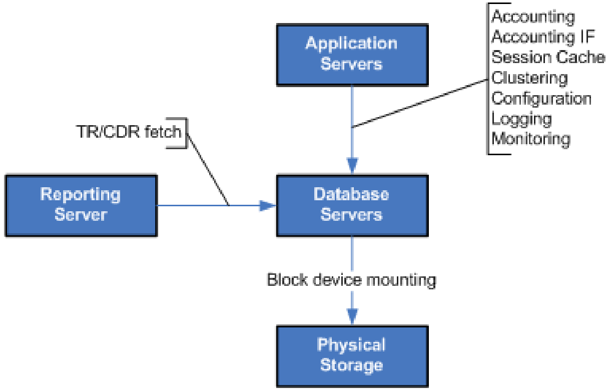
Items	Product 1	Product 2	
Record Size	450Byte/record	Multimedia Message (MM): 150KB - 10MB Short Message (SMS): 160Byte	
Data Retention time	3 months	6 months	
Concurrency	20,000 per second	MM	200 requests/second for writing 1000 requests/second for reading
		SMS	800 requests/second for writing 1000 requests/second for reading
Total data size	**70 TB**	**30 TB**	
Latency	Write delay < 10ms Reporting < 5 minutes	MM	reading delay < 0.2s, writing delay <0.4s
		SMS	reading delay < 0.1s, writing delay < 0.2s
Throughputs	72 Mbps for writing 584 Mbps for reading (1hour) 14.4 Gbps for reading (1day) 432 Gbps for reading (1month)	MM	1.228 Gbps for reading 246 Mbps for writing
		SMS	1 Mbps for reading 1.28 Mbps for writing

NOKIA

Existing Solution and Disadvantage



Oracle database &
EMC disk array

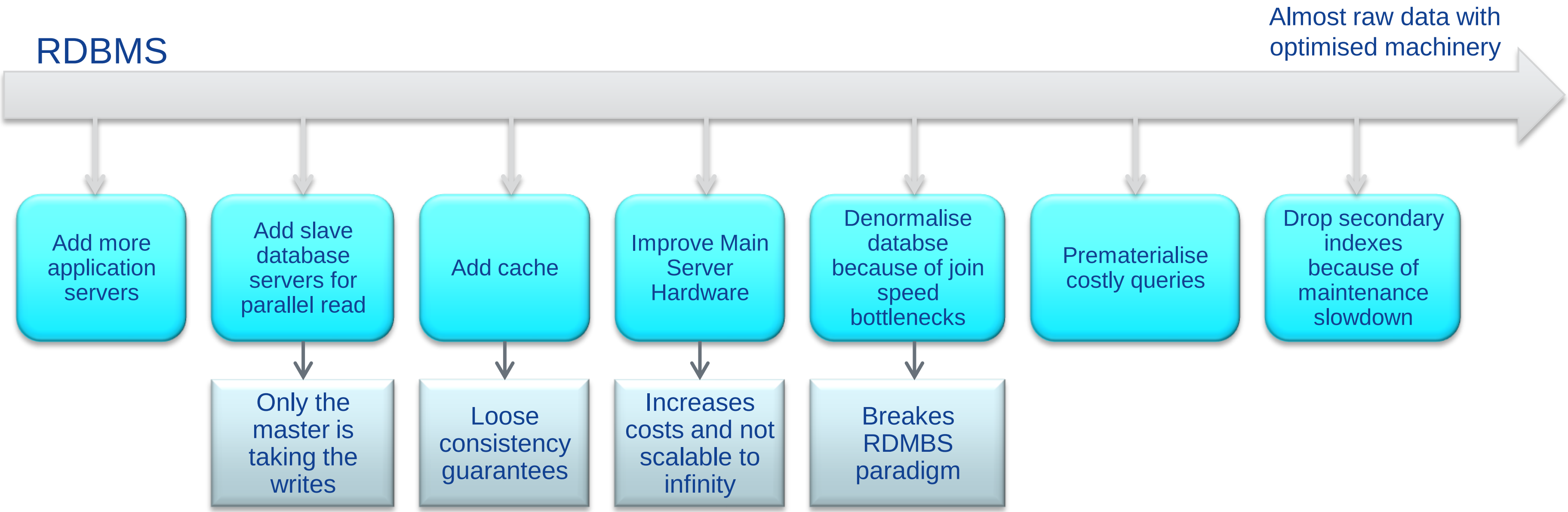


- Traditional RDBMS became bottleneck for Big Data storage and processing

- Low performance in Data Intensive application, e.g. Generating business reports through big data analysis

- Incapable Scale-In/Out for ever-increasing data volume

RDBMS Scaling



NOKIA

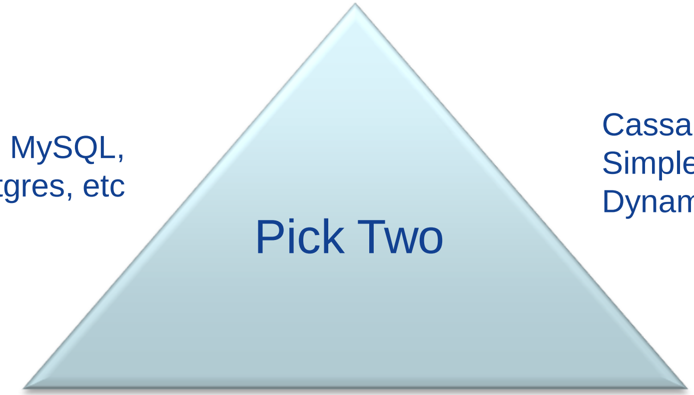
CAP Theorem

a guarantee that every request receives a response about whether it was successful or failed

Availability

MySQL, Postgres, etc

Cassandra, SimpleDB, Riak, Dynamo, etc



Consistency

all nodes see the same data at the same time

MongoDB, Hbase, BigTable, Redis, etc

Partition Tolerance

the system continues to operate despite arbitrary message loss or failure of part of the system

Hbase

Open source, distributed sorted map datastore

- Open source: Apache 2.0 license
- Distributed
  - Store and access data on 1-700 commodity servers
  - Linear scaling of capacity and IOPS by adding servers
- Sorted Map Datastore
  - Not a relational database
  - Tables consists of rows, each of which has a primary key (row key)
  - Each row may have any number of columns – like a `Map<byte[], byte[]>`
  - Rows are stored in sorted order

Sorted Map Datastore

Implicit PRIMARY KEY in RDBMS terms

Data is all `byte[]` in HBase

Row key	Data
cutting	info: {'height': '274cm', 'state': 'CA'} roles: {'ASF': 'Director', 'Hadoop': 'Founder'}
tlipcon	info: {'height': '170cm', 'state': 'CA'} roles: {'Hadoop': 'Committer'@ts=2010, 'Hadoop': 'PMC'@ts=2011, 'Hive':'Contributor'}

Different types of data separated into different „column families"

Different rows may have different sets of columns (table is sparse)

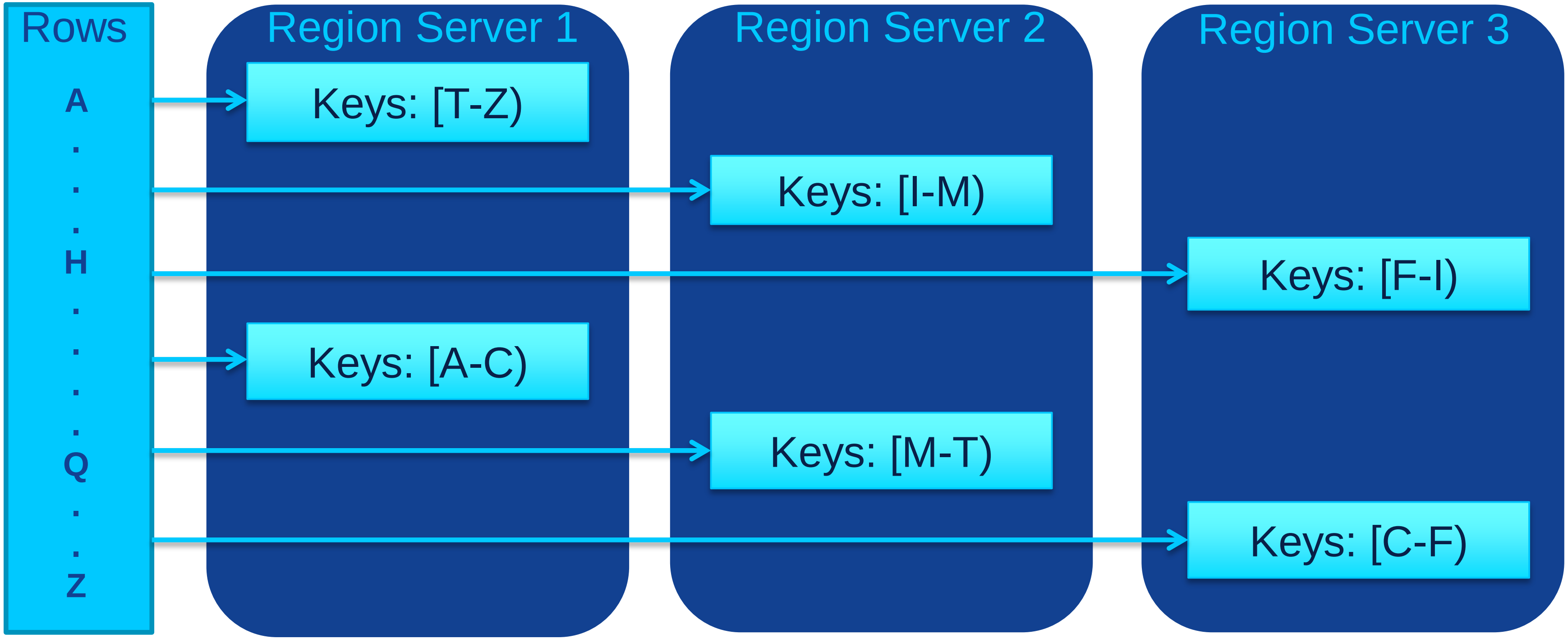
A single cell might have different values at different timestamps

NOKIA

Scalability with Regions

- Table contains sorted rows and dynamically splitted into regions
  - Rows stored in byte-lexicographic order based on rowkey
  - Somewhat similar to Relational DB Primary Index (always unique)
- Region is a continuous set of sorted rows
- Hbase ensures that all cells of the same rowkey are all on the same server

Table and Regions



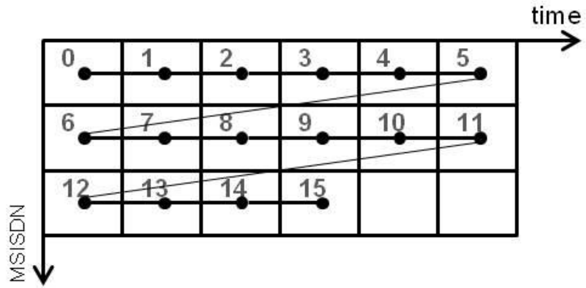
NOKIA

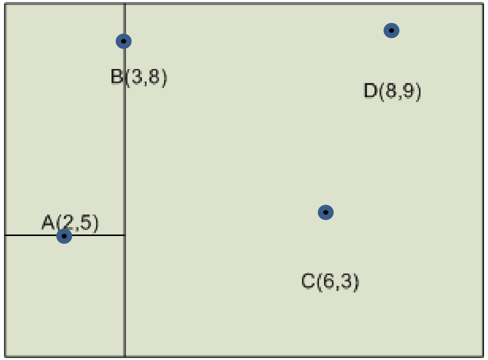
Hbase Query Methods

- Get
  - Retrieves a single row using a rowkey
- Scan
  - Scans the full table
- Range
  - Retrieves a range of rows between a given startRow and stopRow

Challenges

- Handling multi-dimensional data distribution
  - Transformation of data in multi-dimension space to single dimension (*NoSQL/HBase is single rowkey design*)
  - Adopt a linearization technique
- Data Partition
  - Data must be well organized and distributed over nodes to ensure query efficiency and to avoid hotspot in data accessing
  - Pre-defined region instead of automatic region split in Hbase
  - Keep frequently retrieved data stored together to utilize Range Query as much as possible inside of region





NOKIA

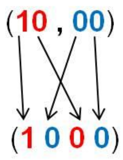
Rowkey Design

Rowkey algorithm by a space-filling curve

- Good extendibility in space size (recursion level and region placeholder)
- Spatial indexing is natively supported (while subdividing, prefix also fit to curve)
- Easy to build up additional indexing on top of it (Prefix Hash Tree, B Tree, KD-Tree etc.)
- Different granularity in sub-space size

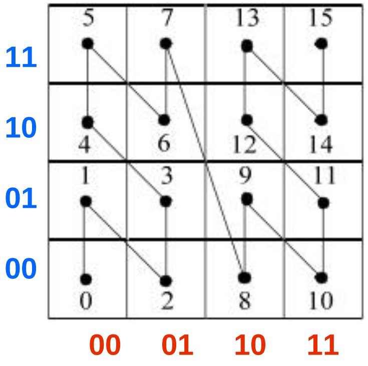
Rowkey algorithm by Z-ordering

- It loosely preserves the locality of data-points in the multi-dimensional space
- Easy to implement.
  - Binary Z-ordering space, bitwise interleaving .
  - Using the Z-order value as rowkey.

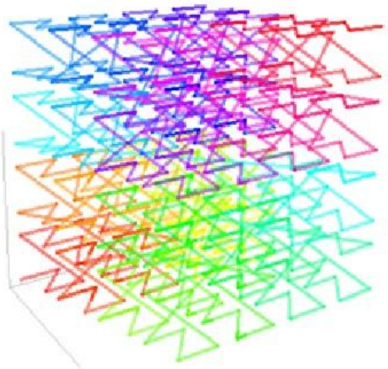


	00	01	10	11
11	0101	0111	1101	1111
10	0100	0110	1100	1110
01	0001	0011	1001	1011
00	0000	0010	1000	1010

Z-order encoding (2-D)



Z-order curve (2-D)



multiple-dimensional Z-order curve

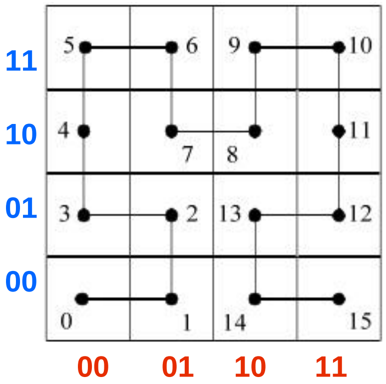
NOKIA

Rowkey algorithm by Hilbert Curve

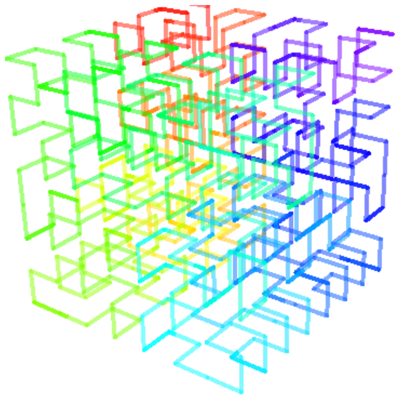
- little complex compared to the Z-order curve
- better one-dimensional continuity

	00	01	10	11
11	0101	0110	1001	1010
10	0100	0111	1000	1011
01	0011	0010	1101	1100
00	0000	0001	1110	1111

Hilbert encoding (2-D)



Hilbert curve (2-D)

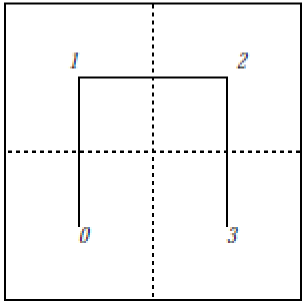


multiple-dimensional
Hilbert curve

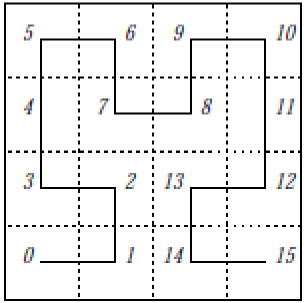
Public

NOKIA

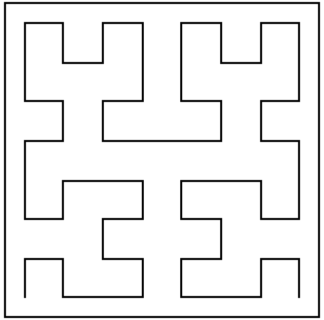
Hilbert Curve Generation



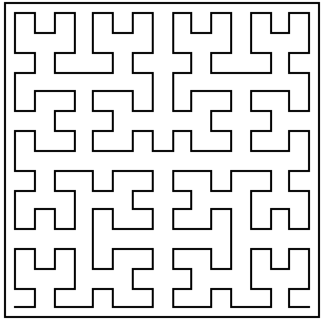
first order



second order

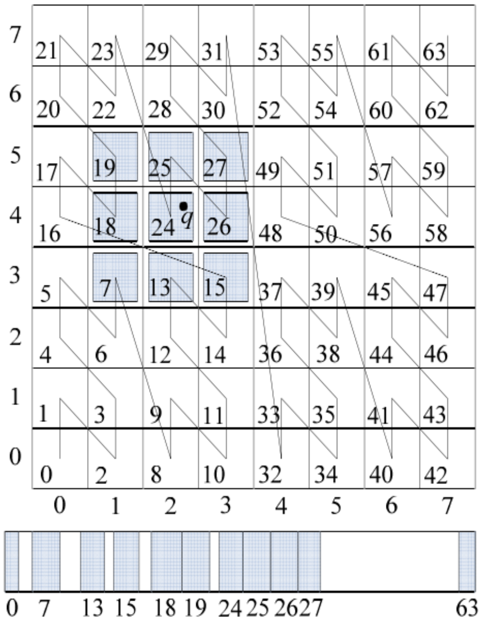


third order

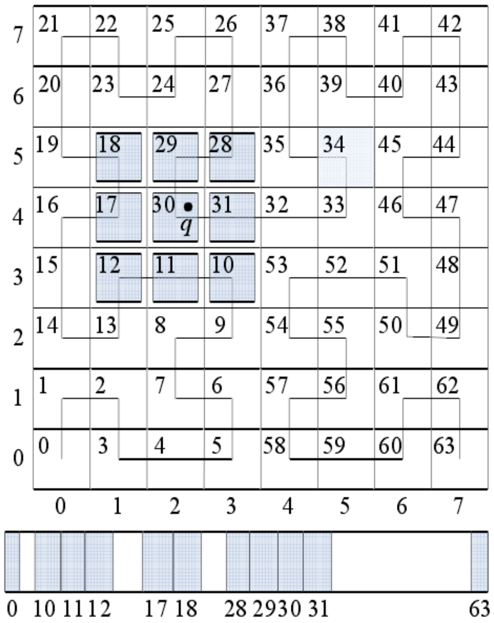


fourth order

Z-order Curve and Hilbert Curve compared



Z-order curve



Hilbert curve

Space aggregation

•Hilbert curve keeps better space aggregation than Z-order curve, which can be seen from left figure.

•For the same region of space, the Hilbert curve has less false-positives than Z-order.

Calculation complexity

•Hilbert curve is more complicated in calculation, which aims to keep the space aggregation of data points.

Data partitioning based on multi-dimension

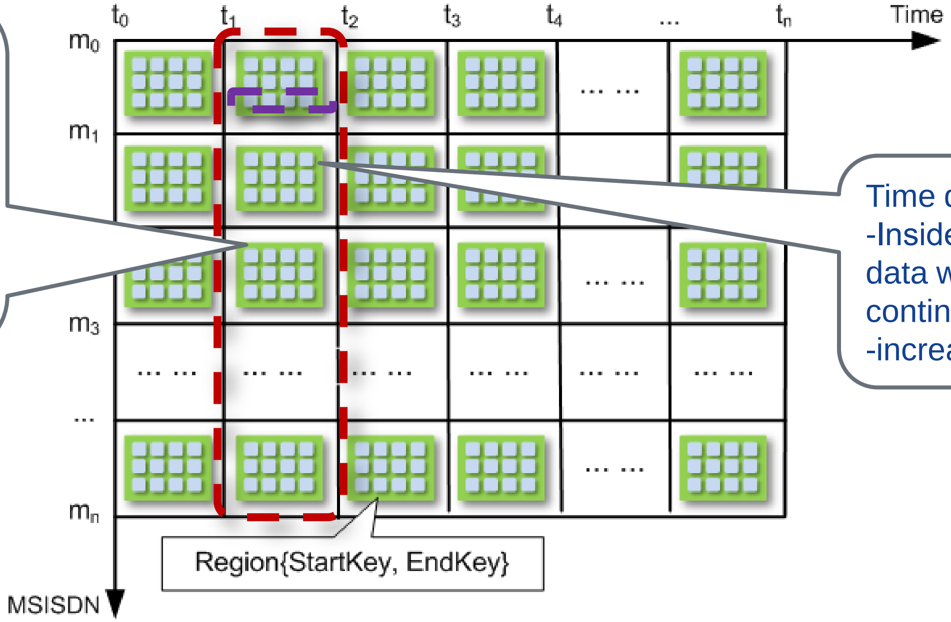
- It can be achieved by pre-defined regions (bucket) in Hbase
  - Automatic region split can't be used in consideration of performance
- Region split solutions
  - Trie-based space split (by the mid-point of dimension)
  - Point-based space split (by the median of data points)

NOKIA

Data Partitioning

Two dimensional data distribution by time and MSISDN

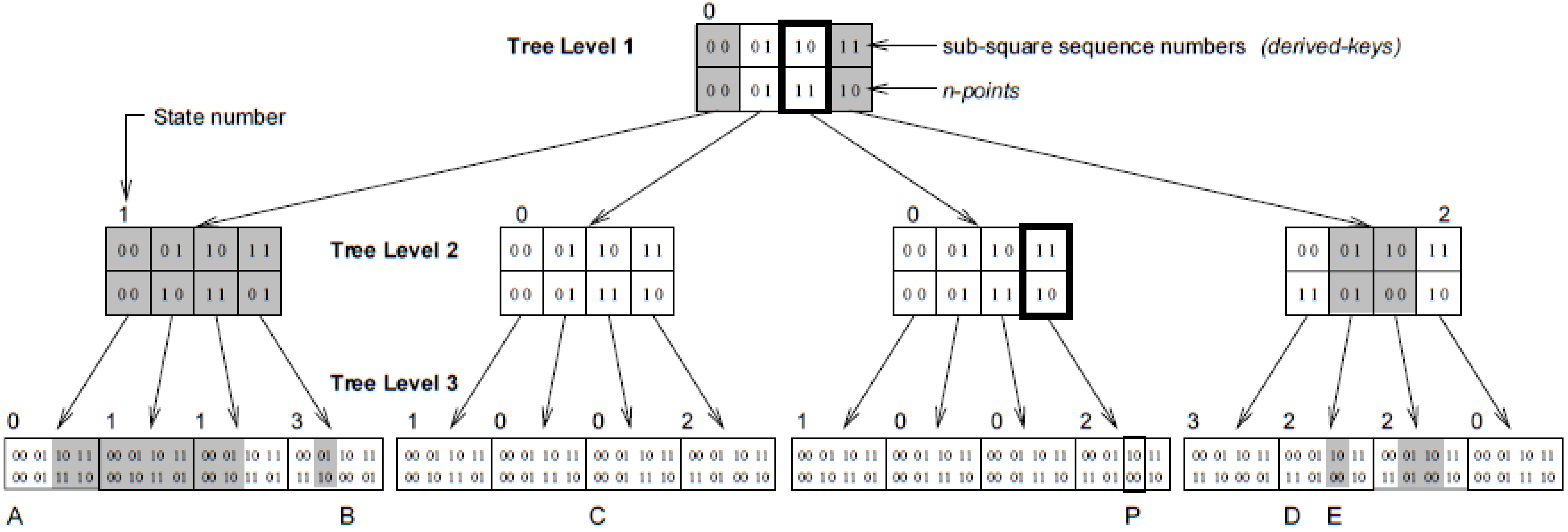
MSISDN dimension:
-users' data will be evenly distributed to different regions
- avoids the Writing Hotspot in case of high concurrent data insert (20,000 per second)



Time dimension
-Inside a region, one users's data will be written in a time continuous way
-increases query efficiency

NOKIA

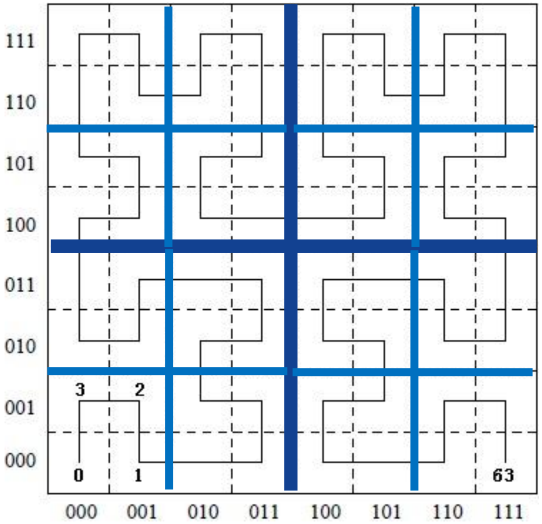
Binary Tree for Hilbert curve



Public

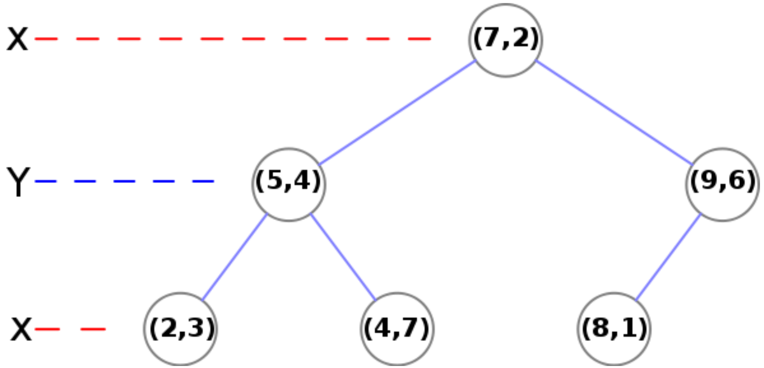
NOKIA

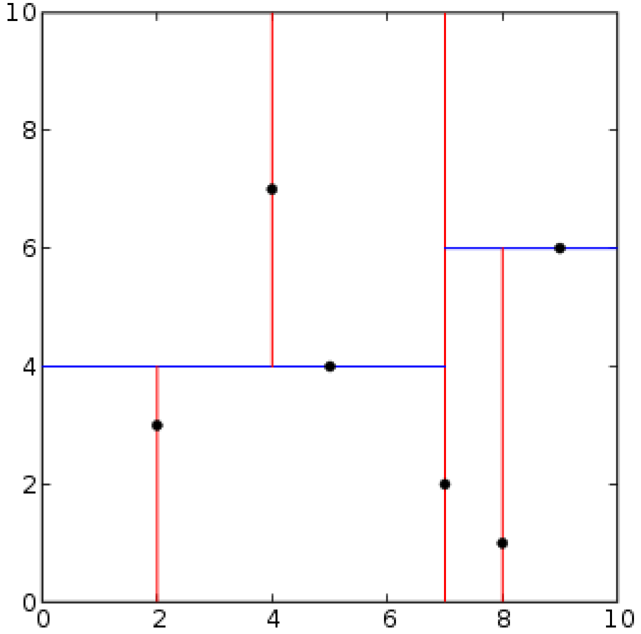
Data Partition: Trie-based region split



- splits the space at the mid-point of all dimensions
  - equal size splits in space-filling curve
  - each subspace uniquely corresponds to a segment of the curve.

KD-Tree





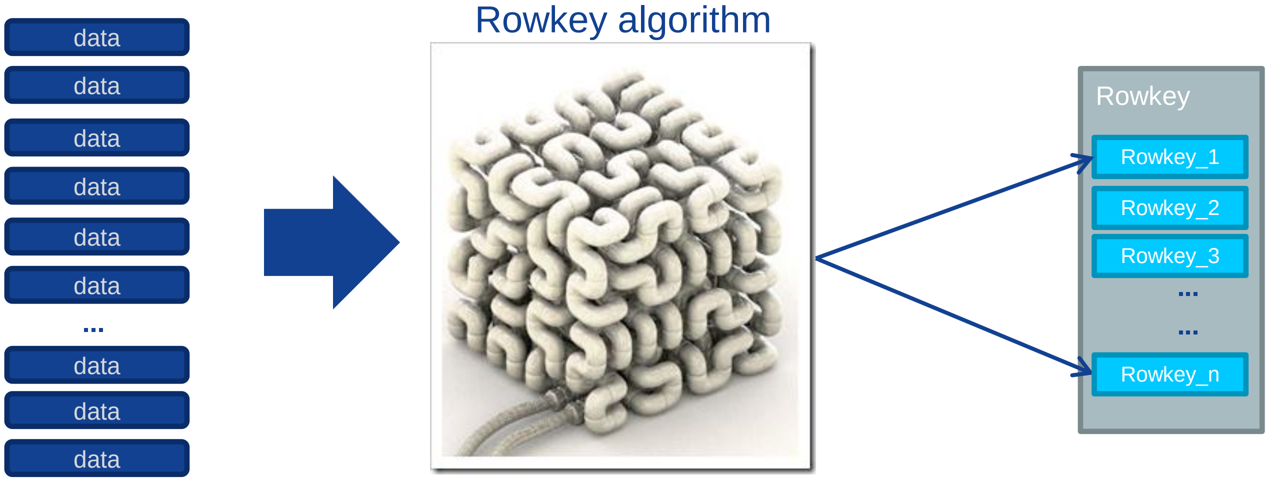
- Splits the space by the median of data points
- Results in subspaces with equal number of data points
- Data point distribution must be known beforehand to select median

Solution and Results

NOKIA

Rowkey algorithm based on Hilbert Curve

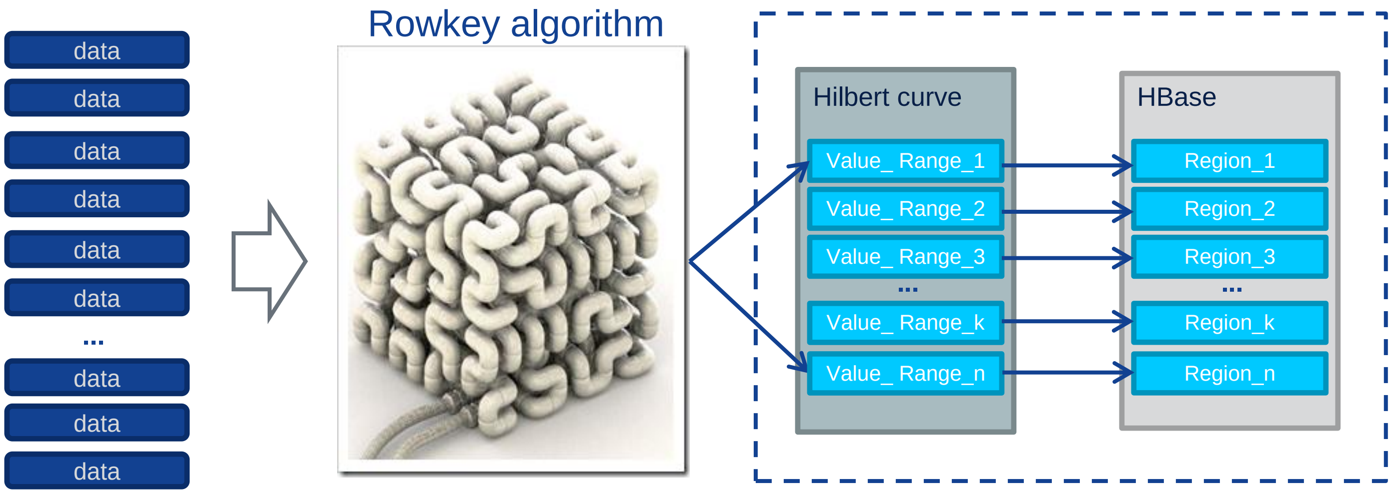
- The rowkey algorithm uses multiple data attributes to generate Hilbert curve.
- Each value in Hilbert curve represents the rowkey in HBase.



Public

Trie-based region split

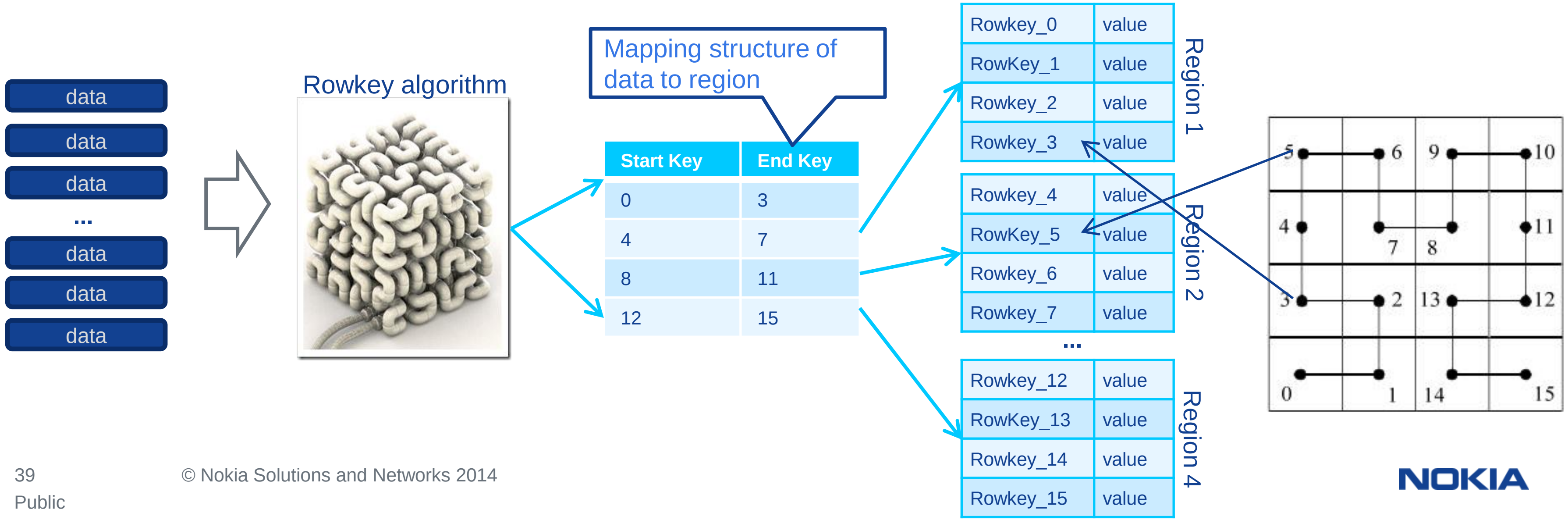
- Selecting the middle-point of each dimension to make customized region pre-split
- Each segment represents a range Hilbert value and corresponds to a region.



NOKIA

Data Distribution

- HBase table is divided into multiple data regions, and each region contains a part of data (multiple rows), which have continuous rowkey in value.
- The region is represented by startkey and endkey, and it takes one row in .META. table of HBase (the row also contains other information related to this region). Our approach uses the .META. table as mapping structure to distribute user data across all regions.

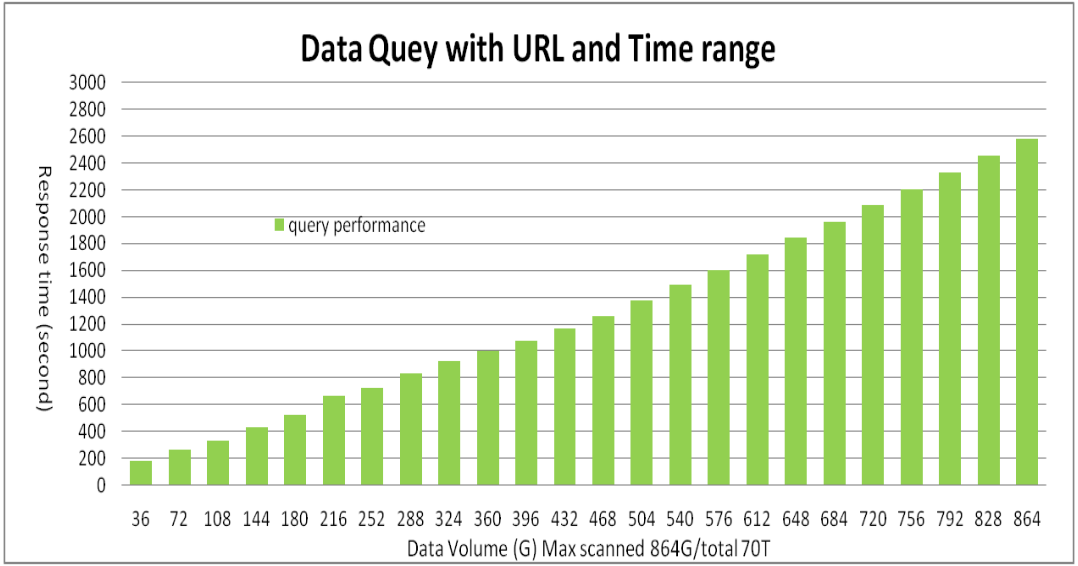


Start Key	End Key
0	3
4	7
8	11
12	15

Public

NOKIA

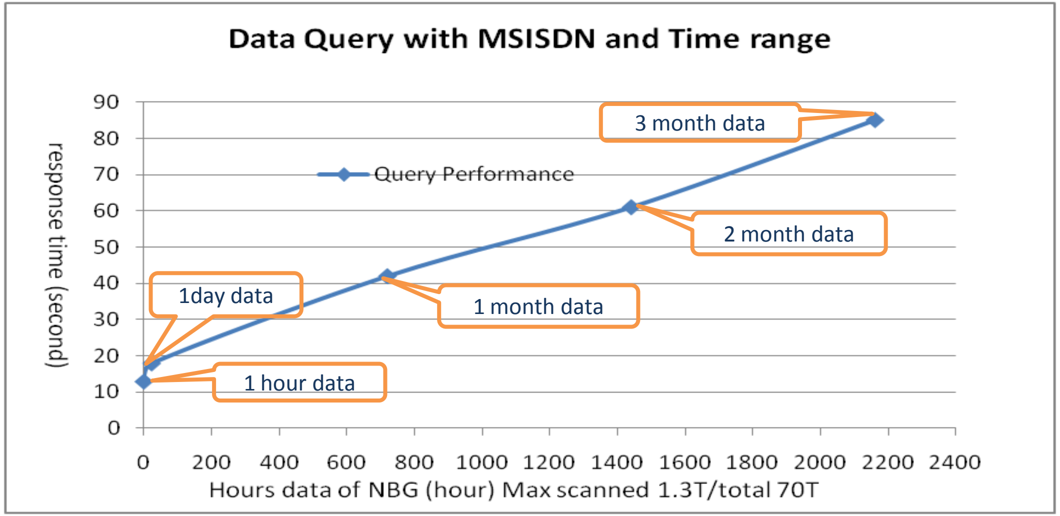
Results – URL Query Performance



- Response time is decreased from hours to minutes (comparing to original Oracle solution)
- ~3x performance speedup after optimizations
- Experiment with 1 master + 8 data node
- Better performance after the extension of nodes and memory

NOKIA

Results – MSISDN Query Performance

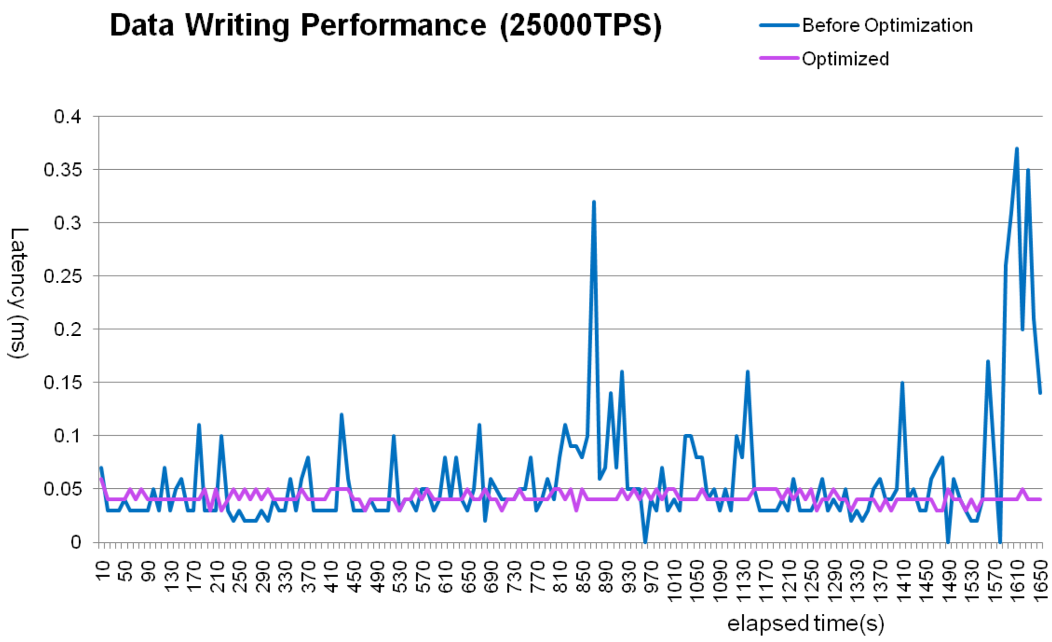


One hour data	13s (1 Map)	13s (1 Map)	Speedup = 1
24 hours data	18s (24 Map)	18s (1 Map)	Speedup = 1
720 hours data (1 month)	33s (8 Maps)	113s (720 Maps)	Speedup = 3.42x
1440 hours data (2 months)	49s (8 Maps)	216s (1440 Maps)	Speedup = 3.54x
2160 hours data (3 months)	60s (8 Maps)	327s (2160 Maps)	Speedup = 5.45x

- 1 minute to scan all data of one subscriber within 3 month, it needs more than 5 minutes before optimization
- 3~5x performance speedup after optimization
- Experiment with 1 master + 8 data node
- Better performance after the extension of nodes and memory

Public

Results – Data Writing Performance



- Data Writing latency is less than 0.05ms on average (requirement is <10ms)
- Before Optimization, region flush, split and compaction will affect writing latency badly, even cause service break
- Region split and compaction storm is avoided by scheduled region compaction, flush and advanced region split, performance curve of high concurrent writing become stable.

Achievement

- Response time of reporting is decreased from hours to minutes comparing to the original Oracle solution
- 4 minutes to scan 2 hours data (144m records) in high concurrency (20,000tps), 3x performance speedup by Hadoop & Hbase optimization
- 1 minute to scan all data of one subscriber within 3 month, 3~5x performance speedup by further Hadoop & HBase optimization
- Writing latency is less than 0.05ms, much less than requirement (<10ms)

NOKIA