ABSTRACT

With the advent of Internet of Things, the field of domain sensing is increasingly being ‘servitized’. In order to effectively support this servitization, there is a growing need for a powerful and easy-to-use infrastructure that enables seamless sharing of sensor data in real-time. In this paper, we present the design and evaluation of Data Quality-Aware Sensor Cloud (DQS-Cloud), a cloud-based sensor data services infrastructure. DQS-Cloud is characterized by three novel features. First, data-quality is pervasive throughout the infrastructure ranging from feed discovery to failure resilience. Second, it incorporates autonomic-computing-based techniques for dealing with sensor failures as well as data quality dynamics. Third, DQS-Cloud also features a unique sensor stream management engine that optimizes the system performance by dynamically placing stream management operators. This paper reports several experiments to study the effectiveness and the efficiency of the framework.

INDEX WORDS: Internet of Things, Servitization, Data Quality, Sensor, Cloud.
QUERY PLANNING & ADAPTATION IN DATA QUALITY AWARE SENSOR SERVICES CLOUD

by

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QUERY PLANNING & ADAPTATION IN DATA QUALITY AWARE SENSOR SERVICES CLOUD

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DEDICATION

To my wife and family, for their endless love, support, belief and encouragement.
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Finally, I am also thankful to EITS for providing me with Graduate Assistantship throughout my masters.
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CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

The Internet of Things (IoT) is expected to transform how we live, work and play. The IoT is set to touch every facet of our lives. We foresee our life with networks of sensors around us that will constantly change and evolve based on our surroundings and inputs from other systems.

Over the last several years, data streaming has emerged as an increasingly important area in the field of computer science, statistical analysis, databases, etc. Data streaming is the transfer of data at a steady high-speed rate to meet the application needs. Some of the stream-based applications include market feed processing and electronic trading on Wall Street, monitoring applications, fraud detections, military applications, etc. Now-a-days sensor data is used for continuous monitoring of the geographical changes or for complex human made systems. Initially sensor based monitoring applications were used only in military but now it has been used in almost every area like ride management, space systems, GPS and the most recent Google driverless car. Sensor data is called as sensor feed and each sensor has a metadata associated to it like location, type of sensor, accuracy, etc.

In order to process real time data, traditional databases have some limitations like high latency for query processing, no approximate query answering, etc. Several traditional software technologies such as main memory DBMS and rule engines have been proposed to address this issue. Many systems like Aurora [14], STREAM [15], etc. have been developed to support the high volume, low-latency stream processing of data. For a system
to be a stream processing engine has to consider certain thumb rules like keeping the data moving, querying on streams, handling stream imperfections, integrating stored and streaming data, processing and responding instantaneously, etc.

Figure 1.1: Basic Architecture of (i) a database system, (ii) a rule engine, and (iii) a stream processing engine.

Based upon the requirement of stream processing engine (SPE), Aurora [14] – a new model and architecture for data stream management (2003), was proposed. The basic job of Aurora is to process incoming streams in the way defined by an application administrator. Aurora in basic is a data flow model consisting of boxes and arrows. Arrow defines the path of the data flow, whereas boxes represents operations to be performed on the data streams. It also supports historical storage to support ad-hoc queries. Aurora also supports query model and its query algebra consists of seven built-in operations for data streaming.
In 2005, inheriting the functionality of Aurora, Borealis [13] stream processing engine has been designed. It is called as a second-generation distributed stream processing engine. Between the years 2003 and 2005, many working prototypes and detailed aspects of technologies such as data modeling, scheduling and load shedding has been developed. However, Borealis focused on the fundamental difference between the requirements of streaming applications and first-generation systems like Aurora. Three fundamental requirements it envisioned in this second-generation SPEs are:

1) Dynamic revision of query results: Ability to process newly available data or updates to revise previously processed imperfect data.

2) Dynamic query modifications: Ability to support low overhead, fast and automatic modifications to change certain attributes of the query at runtime.

3) Flexible and highly-scalable optimizations: Ability to scale and adjust to deal with a large number of devices like sensor devices and perform resource management and optimization.
The main goal is to process high-volume data streams coming from wireless sensor technologies like RFID applications, mobile device services, etc. Furthermore, we expect sensor network to expand exponentially in terms of heterogeneity and volume, hence there is a need of better interface and faster processing power. In summary, Borealis is the system which took all these issues under consideration thereby inheriting core streaming processing functionalities.

There are other systems, like STREAM [15], Fjords [33] which have been developed or proposed in between, but none of the systems can operate over the internet. All these systems are designed to work within the infrastructure like client-based software. Incoming and outgoing of data is also within and in use for self-data analysis, processing and computation.

We are already in the process of making this planet a smarter planet by using sensors and then processing the sensor data to come onto fruitful conclusions. For example, temperature sensor based air conditioners, light sensor based bulbs and tube lights to save electric power and also climate control within the premises, etc. Even if we visualize this, we are actually using the sensor data within the infrastructure with no data sharing between the devices or infrastructure.

Wireless sensor network (WSNs) can be considered and used for data sharing. In this network, each sensor collects the data and forward it to local or base station through network of routers or cluster heads. This set of infrastructure can be used for data sharing but only in limited area. They are not designed to share sensor data in a distributed geographical environment.
Whereas, Sensor web utilizes World Wide Web infrastructure to communicate sensor with sensor or sensor network. This framework defines a suite of web service interfaces and communication protocols abstracting the heterogeneity of sensor (network) communication. There have been an important contribution in this area by projects like IrisNet [10] and SensorWeb [11]. They mainly focus on system and network level optimizations.
In this era of Internet, The Internet of Things is a novel paradigm that is rapidly gaining its place in the world of wireless technologies and sensor web. The basic idea is to use all variety of things or objects like RFID, cell phones, sensors, etc. to collect the data and communicate with each other or with the cloud to meet the common goal. Typically to use Internet of Things as a paradigm, we need sensor data over the internet. WSN still will be considered as a primary sensor network and its base stations will act as a gateway to the cloud or we can say it will have the capability to send the data over the internet.

Figure 1.5: Data over the Internet to user from WSN using base station or sink node.

Also incorporating the properties of Sensor Web, we can come up with a cloud-based sensor data infrastructure or federated sensor data over the cloud. This will allow us to share the data among various heterogeneous sensor devices or applications geographically, which are managed independently, in real time. In summary, we can perceive this as a “Data as a Service” or “Servitization of Data”.

The “Data as a Service” will necessary involve multiple stakeholders such as sensor data providers, users and applications that will consume the sensor data, and the sensor cloud
which will collaborate them all as a complete system. Internet of Things (IoT) paradigm will now revolutionize this infrastructure by sharing and accessing data across the similar or varied domain users or applications over the internet in real time.

Cosm [1] is an early attempt in this area. It provides uploading and downloading of sensor data using RESTful APIs’. However, still data was not available as a service. In other words, we need sensor data as a feed which will be exposed as a service over the Internet. In near future, we can expect data sharing between independent individual providers and consumers. We also expect no direct intervention among them, which can only be fulfilled if we can provide “Data as a Service”. Several data markets like Azure DataMarket [27] and InfoChimps [26], hosts data with the limitation of only static or history data.
CHAPTER 2

QUERY PLANNING & ADAPTATION IN DATA QUALITY AWARE SENSOR SERVICES CLOUD

1 Abhishek Kothari, Vinay Boddula, Lakshmish Ramaswamy, Neda Abolhassani, to be submitted to CollaborateCom 2014 Conference.
ABSTRACT

With the advent of Internet of Things, the field of domain sensing is increasingly being ‘servitized’. In order to effectively support this servitization, there is a growing need for a powerful and easy-to-use infrastructure that enables seamless sharing of sensor data in real-time. In this paper, we present the design and evaluation of Data Quality-Aware Sensor Cloud (DQS-Cloud), a cloud-based sensor data services infrastructure.

DQS-Cloud is characterized by three novel features. First, data-quality is pervasive throughout the infrastructure ranging from feed discovery to failure resilience. Second, it incorporates autonomic-computing-based techniques for dealing with sensor failures as well as data quality dynamics. Third, DQS-Cloud also features a unique sensor stream management engine that optimizes the system performance by dynamically placing stream management operators. This paper reports several experiments to study the effectiveness and the efficiency of the framework.
2.1 INTRODUCTION

It is widely expected that the Internet of Things (IoT) paradigm will enable remote sensing on a massive scale. IoT will comprise of millions or billions of wirelessly-connected sensors that will collaboratively sense various aspects of a given environment. Furthermore, IoT will facilitate dissemination and sharing of sensor feeds on a global scale in near real-time.

Based on recent trends in various computing domains such as storage, software and infrastructure, it is reasonable to expect that IoT will lead to ‘servitization’ of domain sensing functionalities. In such a Sensing-as-Service ecosystem, sensor feeds collected by one party (henceforth referred to as sensor service providers) may be utilized by another party (henceforth referred to as sensor service consumers). In other words, sensor service providers install and maintain sensor infrastructures, and share/trade the feeds from these sensors with sensor service consumers over the Internet. The service consumers can then embed the feeds into their own applications.

There is some initial work on building infrastructures for supporting the sensing-as-service ecosystem. Xively [1] (formerly known as Cosm and Pachube) is an early attempt at such an infrastructure. However, effective servitization requires powerful mechanisms for sensor feed discovery, planning of feed processing workflow (query processing workflow), failure resilience and system management. To the best of our knowledge, most existing infrastructures do not provide these capabilities, thus requiring high-levels of manual intervention. This imposes significant burdens both at service providers’ as well as service consumers ends. Furthermore, although quality of sensor feeds
is critically important for sensing services, the concept of data quality is very weak in most existing infrastructures.

Towards addressing the shortcomings of existing sensor services platforms, in this paper, we present DQS-cloud – a novel cloud-based sensor servitization framework that incorporates advanced feed discovery, feed processing and adaptation capabilities. A unique aspect of DQS-cloud is that the concept of data quality (DQ) of sensor feeds is central to its design. DQ is pervasive throughout the architecture and drives all mechanisms and techniques of the DQS cloud. In designing the DQS-cloud infrastructure, this paper makes three research contributions.

- First, we present a sensor service discovery technique that takes into account the DQ requirements of individual sensor service consumers and the DQ properties of individual sensor feeds. This DQ-aware sensor service discovery technique finds the feed that best matches requirements of individual sensor service consumers both with respect to the content of the feed as well as the quality of the feed.

- Second, we design a DQ-aware technique for planning feed processing workflows. This technique intelligently places feed processing operators on gateway devices as well as cloud servers so as to optimize the bandwidth and battery consumption. Furthermore, our technique incrementally adapts to entry and exit of sensor service providers and consumers.

- Third, we present a DQ-aware fault tolerance mechanisms to deal with failures and recoveries of individual sensors. Our technique minimizes the disruption of service at sensor data consumers. Further, it also reduces the need for human intervention.
We have implemented a real prototype of the DQS-cloud framework. We present several experiments to demonstrate the efficiency and the scalability of the proposed architecture and techniques.

The remainder of the paper is organized as follows. Section 2.2 presents background and motivation on Internet of things and Data as a service. Section 2.3 explains the system architecture of our DQS-Cloud system. In section 2.4, we discuss three novel features of our system in detail. Section 2.5 demonstrates the experimental study of the system. In next section 2.6, we cover the related work followed by conclusions in section 2.7 of the paper.

2.2 BACKGROUND AND MOTIVATION

Internet of Things (IoT) will comprises of billions devices achieving a web where things would be connected, could sense and could communicate with each other. IoT will be true enabler of ubiquitous sensing bringing in dynamic network of billions of devices and will bring further understanding of complex natural processes, efficient management of transport, medical, and infrastructure services, help in effectively reporting and tackling events of interest and many more things. The idea of ‘Computing as Service’ where the cloud providers have successfully catered Platform as a Service (PaaS), Infrastructure as a Service (IaaS) and Software as a Service (SaaS) model has revolutionized the Information Technology industry. It will be very likely that in near future, the cloud based Data as a Service model where either raw data or processed data would be used for key decision making will further expand the ‘servitization’ concept. This will gain popularity as it
clearly has several advantages. First, as in the case of cloud computing it will reduce the cost for individuals by not having to worry about buying own servers and other technical and maintenance overhead. Second, by enabling individuals, domain scientists and businesses to share real time data, the sensor service paradigm will enable easy data transfer on global scale. Third, it will lay foundation stone to sensor service industry where sensing providers would expose their data feed and the middleware would provide appropriate data service to the consumers.

The availability of online data markets such as InfoChimps [26], Azure marketplace [27] data market has validated the Data as a Service model. However, the existing data marketplace host static pre-collected data mostly structured in nature. Our system’s intention is to provide real time data to consumers. Xively [1] is the first effort towards building a real time data sharing cloud platform but there remains some fundamental limitation between the requirements of next generation IoT platform and Xively. First, it supports very primitive query to obtain the data of interest hence it is a tedious process for the user to search the data feed that fits her requirements of various kind. Second, if the user chosen data feed stops providing data due to various reasons, the user needs to go back and redo the entire search of finding appropriate data feed. Such design needs the user to write her own feed monitoring tool. Third, the user remains ignorant if a new data feed with better capabilities gets registered with the cloud server. Ideally, in such case the server itself should choose the best data feed dynamically and provide it to the user, but such facility is missing. Fourth, the concept of data quality is completely missing from such platform, as a result a user has no choice of expressing the application specific feed requirements.
2.3 DQS-CLOUD SYSTEM ARCHITECTURE

In this section, we describe the architecture of our system. The Data Quality-Aware Sensor Cloud system is based on the features of stream and query processing engine, data quality and monitoring. Figure 2.1 shows the high-level architecture of our proposed cloud system.

2.3.1. OVERVIEW

The system consists of three layers, i.e., sensor data providers, subscribers and cloud server. The first layer is the sensor data providers in which providers can vary from cell phone to Raspberry Pi to any of the possible sensor data receiver acting as a gateway as shown in Figure 2.2. To be a provider, a device must have the ability to send sensor data over the Internet. The second layer, subscribers, they may be any device or application that belongs to a company, a department or a gateway to other wireless sensor network. Subscribers basically show interest to collect sensor data in real time for a particular data flow. The last layer, the cloud server is the backbone of our DQS-Cloud system as shown in Figure 2.1. Different components exist on the server functioning and working continuously to process the data, keeping an eye on the quality of the data, processing query, and operations in real time.

Figure 2.2 demonstrates a high level architecture of a provider. We use the terms provider / publisher and data stream / sensor interchangeably throughout the paper. Devices such as Raspberry Pi, cell phones are considered as providers because they can connect to the Internet. Small appliances such as temperature, humidity, wind, and heart rate monitor
sensors are those that actually collects the data. Each of these devices are connected to the providers to transmit data over the Internet. The channel of data points for each small devices is termed as data stream. Many data streams can be supported by a service provider.

Figure 2.1: DQS-Cloud System Architecture

A key component of our architecture is the Data processing and Query Layer. It is responsible for maintaining DQ aware catalogs, DQ aware sensor feed discovery, dynamic allocation and de-allocation of buffers, the operations to be performed on data streams and control the status (active / passive) of the data streams. The Publisher Interface component is responsible for the registration of data providers and streams. It also informs the data stream on its new frequency and delay time interval calculated by the Data processing and Query layer. The next component is the Subscriber Interface, which is responsible for the registration of subscribers, maintaining metadata for each subscriber and sending data in real time to the subscriber in question provided by the Data processing and Query layer.
The next component is the **Quality Monitoring component**, which is designed to monitor data streams. It checks whether the data stream meets the requirement for which they have agreed during registration. Some of the quality parameters that we consider are data stream polling, the delay time and frequency interval. The other monitoring component is **Subscriber Monitoring** whose task is same as that of Quality Monitoring component except that it oversees the data processed by the **Data processing and Query layer** exclusively for the specific subscriber. The quality parameters are also the same as mentioned previously.

The last component is **Data layer**, which is composed of in-memory buffers and database comprising of metadata and history information. The **Buffers** are responsible for storing the recent sensor data feeds to allow real-time processing. The **Metadata** database stores the information of all subscribers, data providers and data flows. The system also has a **History** database which is responsible for storing the data points of all data streams. This is useful for batch processing and serve ad-hoc queries.
2.3.2 DATA QUALITY MODEL

Our main objective is to make a DQ as a multidimensional space considering all sensor devices have multiple quality parameters or metadata like accuracy, delay, frequency, latitude, longitude, sensor type, etc. In addition, the sensors are susceptible to failure which entails the data quality as an important factor to be considered for DQS-Cloud. There is no limitations on the number of quality parameters, but our current system has limited the parameter to few and can readily be adapted to other factors effectively. The quality parameter, Accuracy represents how close the data values of the sensors are to the real values. The Delay is the time interval after which provider sends the data to the cloud server. Frequency is the time interval after which the sensor collects data points or values. Location of sensor is the combination of latitude and longitude. Sensor types are as temperature, humidity, light, wind sensors, etc.

With this model, each individual sensor feed maps to a specific point in the multidimensional space at any given point of time. The coordinates of the point to which a feed is currently mapped depends upon the current values of its DQ attributes. On the other hand, each domain application maps to a region (sub-space) of the multidimensional space. This subspace indicates the value ranges along various DQ dimensions that are acceptable to the domain application. With this model, a particular sensor feed, say \( S_i \), satisfies the DQ constraints of a domain application \( DA_k \), if \( S_i \) maps to a point that falls within \( DA_k \)'s sub-space. Figure 2.3, illustrates our multidimensional DQ model, in this example, \( S_2 \) satisfies the DQ requirements of \( DA_1 \), whereas \( S_1 \) does not.
Apart from the multidimensional space, a DQ model should have some characteristics as mentioned below but are not limited to:

(i) Effectively accommodate a diverse and possibly growing set of DQ attributes.

(ii) Quickly determine the feeds that satisfy the DQ requirements of particular domain applications or subscriber.

(iii) Compare sensor feeds based on their DQ characteristics.

2.3.3 QUERY LANGUAGE

DQS query language is used to describe both subscriber the kind of data they need, as well as the provider to describe the feeds they provide. There are several ways to represent the query in the form of XML [29], JSON [28] and CSV.
Our system allows to write the query language, either in JSON or XML. In general, the syntax of the query contains two main parts.

i. Description of attributes - sensor type, latitude, longitude, etc.

ii. The attributes of data quality - delay (milliseconds), frequency (milliseconds), accuracy, etc.

For a provider, the description attribute describes the kind of data that is being served along with geolocation sensors and data quality attribute that describes the ability of quality of sensor data. While for a subscriber, the description attribute specifies the kind of data and the geolocation the subscriber is interested in along with the data quality attributes that describes the data quality requirements of specific application.

Figure 2.4 shows an example of the JSON query language. There are other ancillary attributes in the query language running on our system, but is not described here.

```
<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>hostname</td>
<td>127.0.0.1</td>
</tr>
<tr>
<td>Port</td>
<td>5556</td>
</tr>
<tr>
<td>qDataStream</td>
<td>temperature</td>
</tr>
<tr>
<td>qLatitude</td>
<td>33.955788</td>
</tr>
<tr>
<td>qLongitude</td>
<td>-83.3823876</td>
</tr>
<tr>
<td>qAccuracy</td>
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</tr>
<tr>
<td>qDelay</td>
<td>100000-240000</td>
</tr>
<tr>
<td>qFrequency</td>
<td>20000-60000</td>
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</table>
```

```
<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DatastreamId</td>
<td>temperature</td>
</tr>
<tr>
<td>Unit</td>
<td>Celsius</td>
</tr>
<tr>
<td>Accuracy</td>
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</tr>
<tr>
<td>Frequency</td>
<td>50000</td>
</tr>
<tr>
<td>Delay</td>
<td>150000</td>
</tr>
<tr>
<td>Tags</td>
<td>temperature, temp</td>
</tr>
<tr>
<td>Latitude</td>
<td>33.955788</td>
</tr>
<tr>
<td>Longitude</td>
<td>-83.3823876</td>
</tr>
</tbody>
</table>
```

**Subscriber Query**

**Publisher Description**

Figure 2.4: Query Language.
2.4 DATA QUALITY AWARE TECHNIQUES

All techniques to be discussed are highly integrated and coupled to perform various autonomic operations like choosing an optimized data stream, failure detections, bandwidth optimization, etc. in our DQS-Cloud system.

2.4.1 DATA QUALITY AWARE SERVICE DISCOVERY

The main purpose of this feature is to optimize the number of active data streams. The optimization is performed by choosing the appropriate data stream for subscribers maintaining awareness of quality data. The importance of data quality for sensor data requires a way to establish a mechanism for introducing data quality parameters in the cloud system. Systems like Xively [1], can provide sensor data, but do not consider the quality of the sensor devices and data. Apart from the quality of the data, the current sensor cloud platform require subscribers to manually perform the tasks of choosing providers, which is a very difficult task to handle.

![Figure 2.5: Illustration of data quality aware service discovery and query planning.](image)

We used two techniques to carry out the aforementioned limitations of other systems. First, without the subscriber’s intervention, our system incorporates automated technique for choosing an optimized data stream for the subscriber based on query’s DQ
parameters. For example, if subscriber $S_i$ wants to receive sensor data of type $t_i$ with frequency $f_i$ and the delay interval $d_i$ of a particular location $l_i$. The subscriber has to manually do the lookup to select a data stream $D_i$. Basic systems do not guarantee availability of exact data streams, as a result the subscriber may have to choose an optimized data stream up to the threshold for each of the DQ parameters. Given this, our system chooses $D_i$ on the fly which will be either exact or optimized feed for the subscriber $S_i$. This process is automated without the intervention of the subscriber. To select a data stream for many subscribes, the system selects the one that is better able to meet the need of as many subscribers. In DQ 3-dimensional model, where the parameters of DQ are accuracy, delay and frequency, we chose a data stream with the lowest frequency, the exact accuracy and delay which is within the threshold of the subscriber. For example, in Figure 2.5, both data streams $D_1$ and $D_2$ are within the DQ sub-space of subscriber $S_1$. Our system chooses data stream $D_1$ because it has the minimum frequency interval of 10,000 milliseconds.

Second, several subscribers which have similar queries, a single data stream can be used to meet their needs. For example, the subscriber $S_i$ and $S_j$ both want to receive data from sensors with type $t_x$, frequency $f_x$, and delay $d_x$ of a particular location $l_x$. In the basic system, for both the subscribers, human intervention is required to choose the data stream. Therefore, in the worst case, they are most likely to choose different data streams, assuming that the system has many streams that can meet their needs. This means for the subscriber $S_i$ and $S_j$, $D_i$ and $D_j$ data stream has been chosen, respectively. However, in our case, the number of active data streams for similar subscribers are reduced efficiently. This reduction is due to the selection of already active data streams. For the above example, our system
tweaks the DQ parameters of one of the data streams by performing some operations, so that it can satisfy the need for both \( S_i \) and \( S_j \) subscriber within their thresholds, respectively. In Figure 2.5, as discussed before, our system chooses data stream \( D_1 \) for subscriber \( S_1 \). We can see that both data stream \( D_1 \) and \( D_2 \) are also within the sub-space of subscriber \( S_2 \). However, our system chooses data stream \( D_1 \) as it is already active. Thus, it results in fewer data streaming for ‘m’ subscribers considering data quality awareness. We have also shown this in the experimental section 2.6.3.

Using the above techniques, our system also gains more control over providers and subscribers, which can help us in handing of data stream failures dynamically. Also, since we have control on the choice of the data stream to keep active, we can easily switch from one data stream to another on the fly even when the server and the subscribers are up, running and listening. We will discuss more about this in detail later.

2.4.2 QUALITY AWARE QUERY PLANNER

The main purpose of this feature is to plan the query effectively. These queries include DQ characteristics that must be considered when selecting a sensor feed for a subscriber. We have already discussed how to discover feeds, but the next challenge is deciding where to place the quality operators such as filter, sampler, etc. The optimized decision should facilitate a lower consumption of bandwidth of the network between providers and cloud server and cloud server and subscribers, respectively. The number of data points required per subscriber can be calculated as:

\[ S_i n = \frac{\text{SubscriberDelay}(S_i d)}{\text{SubscriberFrequency}(S_i f)} \]
Similarly, number of data points transferred per data stream of the provider is:

\[ D_{in} = \frac{\text{DatastreamDelay}(D_{id})}{\text{DatastreamFrequency}(D_{if})} \]

To reduce bandwidth consumption on the network between providers and cloud server, a certain level of operators have to be pushed to the end of the provider. Our system achieves this by using two-step procedures. First, it reduces the number of data points per data stream of a provider. For example, subscribers \( S_i \) and \( S_j \) both want to receive sensor data of type \( t_x \) with frequency \( f_i, f_j \) and of delay \( d_i, d_j \) of a particular location \( l_x \), respectively. Both queries are similar but with different delay parameters and frequencies. In the basic system, both queries will be considered as different and choose two different data streams. As we know, \( D_{in} \) must be greater or equal to \( S_{in} \), otherwise the data stream \( D_{in} \) cannot be selected for the subscriber. Thus, the number of data points to transmit will be more than the desired, i.e. \( D_{in}, D_{jn} \) for subscriber \( S_i, S_j \), respectively. Whereas in our system, which has DQ aware operators, the important task is to decide which operators should be pushed to providers for data streams. For each subscriber, we push the values of the corresponding DQ parameters and perform operations on providers. Thus, transmitting only the selected data points \( S_{in}, S_{jn} \) as needed. Therefore, we have reduced the number of data points from \( \Sigma D_{kn} \) to \( \Sigma S_{kn} \), where \( k \in 1 \) to \( m \) and ‘\( m \)’ is number of subscribers. In Figure 2.5, for both subscribers \( S_1 \) and \( S_2 \), data streams \( D_1 \) and \( D_2 \) are selected, respectively. Our system computes new delay interval for \( D_1 \) and \( D_2 \) as 50,000 milliseconds and 60,000 milliseconds, respectively and new frequency interval as 250,000 milliseconds and 240,000 milliseconds, respectively. So, the number of data points are reduced from 134 to 37 per 1,000,000 milliseconds.
The second step uses incremental approach by annotating the active feeds or data streams. As we discussed in sub section 2.4.1, we reduce the number of active data streams by calculating new values for the DQ parameters. Thus, for the above scenario, since both queries are similar, only one data stream is needed. The calculated value is the minimum of each DQ parameters of all subscribers to a data stream. If the data stream $D_i$ is selected for both the subscribers $S_i$, $S_j$, a new value for the DQ parameter of a data stream is calculated. For example, $D_{id}$ and $D_{if}$ have new value equal to $\min (S_kd)$ and $\min (S_kf)$ where $k \in 1$ to $m$, respectively. With this approach, the data stream transmits $D_in$ using new calculated values, which is less than or equal to $\Sigma S_kn$. In Figure 2.5, data stream $D_1$ is within the sub-space for subscribers $S_1$ and $S_2$. The data stream $D_1$ is selected for both as per the data quality aware service discovery mechanism. The computed delay and frequency interval for $D_1$ is 50,000 milliseconds and 240,000 milliseconds, respectively. Hence, the number of data points are further reduced from 37 to 20 per 1,000,000 milliseconds.

However, to reduce the bandwidth between the cloud server and the subscriber, we do not send extraneous data points to the subscribers. Using above two steps, data stream $D_i$ sends $D_in$ data points, which is greater than or equal to $S_kn$, where $k \in 1$ to $m$. So we have a second level of quality operators in the cloud server, to send only data points using the selected or annotated data stream. Now, the second level of planning occurs at Data processing and Query layer to send only the request quality aware data points to the respective subscribers. Therefore, we apply such as filter, sampler, etc. for each subscriber. In the above case, for subscribers $S_i$ and $S_j$, with the second level of query planning, we transmit only data points $S_in$ and $S_jn$, respectively, from the cloud server. Therefore, we
have reduced the number of data transmission from the cloud server to subscribers from $mD_n$ to $\Sigma S_kn$, which is the desired number of data points.

By using the above mentioned approaches we are able to meet the needs of all subscribers without losing any DQ aware threshold. Along with that we also reduce the bandwidth consumption of the network between providers and cloud server. We also demonstrate this experiment in section 2.6.4.

### 2.4.3 FAILURE RESILIENCE AND ADAPTATION

The most important aspect of this feature is to detect failures of both providers and subscribers and dynamically adapt to the new environment efficiently. Some of the situations in which the provider or the subscriber may stop responding may be fluctuations in network bandwidth, a malfunction of the sensors, the battery drain, power outage, etc. Current systems such as Xively [1] do not address such failures. If the data stream or the provider fails, the subscriber has to manually choose a new data stream again. Our system through *Quality Monitoring* and *Subscriber monitoring* component, detects faults of both data streams and subscribers respectively. Both of these glitches are reported to *Data processing and Query layer* and the system performs autonomic computing. Considering DQ-aware aspects, tasks as choosing a new data stream for an active subscriber, changing the delay time interval and frequency of data streams and updating the status (active / passive) of data streams and subscribers are taken care exclusively by this feature.

Our system deploys a very small application at the provider’s end for each data stream allowing us to control them. With this application, after each polling interval each
of the data stream polls to control new value of DQ parameters. Our system initially sets the delay interval for each data stream to 0. This means that the system does not need the data of this data stream. Therefore, we can deduce that if a data stream delay is set to 0, it is in passive state, otherwise in active state. We activate a data stream if and only if a subscriber needs it.

Figure 2.6: Illustration of failure resilience and adaptations.

Providers such as sensing devices are highly susceptible to failures. We need such a mechanism that maintains a minimum data reception interruption without fail for the subscribers. For minimal disruption, our system continuously monitors each data stream, regardless of their status (active / passive) and autonomously adjust to the new need. We monitor the polling of each data stream. If for any data stream our Quality Monitoring detects that it is probing for a certain period of time, we believe that the data stream is not functioning and sets its delay time interval to 0. However, our system was already using this data stream to meet the need of some subscribers. For such scenarios, our system adapts autonomously and select a new data stream for these subscribers with minimal disruption. While performing this task, the subscriber may not receive data for certain time. Our system ensures that the subscriber receives data within their DQ thresholds or report about current data stream failure with no other data streams satisfying the need. If the subscriber
is still willing to wait, the system sends the data as soon as we have a data stream for it. In Figure 2.6, as discussed for previous two features, D₁ is selected for both S₁ and S₂. The computed delay and frequency interval for D₁ is 50,000 milliseconds and 240,000 milliseconds, respectively. If data stream D₁ stops functioning properly and our system detects it, then for both subscriber S₁ and S₂ we need to choose a new data stream. As a result, our system chooses a data stream D₂ for both the subscribers as it is within their DQ sub-space.

Similarly, subscribers can also be prone to failure especially if they are sensor devices. Our system's Subscriber Monitoring component detects the failure by checking heartbeat of all subscribers after a certain time interval. Once the failure of a subscriber is detected, the count of the number of subscribers is reduced for a data stream of a provider. This way the system can decide whether to keep data stream active or passive. For example, after a failure of subscribers, none are left for a data stream, we set the delay of this data stream back to 0. However, it may be the case that other subscribers are still active in the system and use this data stream, so the system still keeps it in active state. The important task in this case is to calculate new values for the DQ parameters of a data stream. The system will choose minimum value of DQ parameter of all the corresponding subscribers as noted above. Recalling how we choose the DQ parameter value for the data stream, the system may have to compute new values for its DQ aware parameters. In Figure 2.6, data stream D₁ is selected for both subscriber S₁ and S₂. The computed delay and frequency interval for D₁ is 50,000 milliseconds and 240,000 milliseconds, respectively. If subscriber S₁ stops functioning properly and our system detects it, then for data stream D₁ the number
of subscribers reduces to 1. The new computed delay and frequency interval for $D_1$ is 60,000 milliseconds and 240,000 milliseconds, respectively.

Using the mechanism of direct supervision and coordination of the monitoring components with *Data processing and Query layer*, our system can withstand failures and dynamically make DQ aware adjustments.

### 2.5 EXPERIMENTS

In this section, an experimental study of our DQS-Cloud system is presented. The objective of this experiment is to demonstrate:

i. The dynamic nature of the system.

ii. Optimization incurred in terms of number of active data flows and bandwidth consumption.

iii. The efficient working of our system.

We have implemented this prototype from scratch in Java using Java SE SDK 1.7. In order to replicate real-world scenario, we have implemented a client-based architecture where the clients are *providers and subscribers*, while the server is our *cloud server*. All providers, subscribers and server are on different machines of different platforms to consider heterogeneous environment.

For the experiments, the server uses i7-3630QM processor Intel ® Core ™ clock speed of 2.4 GHz machine having main memory of 12GB and a cache memory of 6MB. The machine operates on the platform of Microsoft Windows 8. The publishers and
subscribers machines are running on Windows, Linux, and UNIX operating systems. For persistent storage on the server, we have used MySQL 5.6. The provider generates synthetic data for each data streams and stores the data in the lightweight SQLite database [30] in real time. To consider the network latencies we positioned publishers, subscribers and server geographically.

2.5.1 REFERENCE TABLES AND ASSUMPTIONS

In all experiments below, we consider data streams and similar subscribers, so there will be at least one possible match for each subscriber. We assume that all data quality parameters are satisfied except for the frequency and delay interval. Table 2.1 and 2.2 shows the data streams and subscribers are used for experiments along with their corresponding frequency and delay time intervals. All mentioned time intervals are in terms of seconds.

Table 2.1: List of data streams considered for experiments.

<table>
<thead>
<tr>
<th>Data Stream</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
<th>D7</th>
<th>D8</th>
<th>D9</th>
<th>D10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Int.</td>
<td>50</td>
<td>25</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>10</td>
<td>40</td>
<td>30</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Delay Int.</td>
<td>150</td>
<td>100</td>
<td>150</td>
<td>100</td>
<td>180</td>
<td>200</td>
<td>120</td>
<td>60</td>
<td>180</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 2.2: List of subscribers considered for experiments.

<table>
<thead>
<tr>
<th>Subscriber</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
<th>S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Int.</td>
<td>50</td>
<td>60</td>
<td>40</td>
<td>40</td>
<td>50</td>
<td>12</td>
<td>11</td>
<td>30</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Delay Int.</td>
<td>250</td>
<td>240</td>
<td>200</td>
<td>200</td>
<td>100</td>
<td>240</td>
<td>330</td>
<td>90</td>
<td>80</td>
<td>140</td>
</tr>
</tbody>
</table>
2.5.2 TIME TAKEN TO SEND FIRST DATA POINT TO SUBSCRIBER

In general, the subscriber has to manually select an active sensor feed from the list of sensor feeds as in the case of Xively [1]. Also, the subscriber does not know when it will receive its first data point. Whereas, our system has an ability to choose a data stream on the fly and send the subscriber first data points as discussed below:

1) When the selected data stream is passive, the first step is to make the data stream active and then the active data stream sends data according to the delay time calculated by the *Data processing and Query layer*. Since the clocks are not synchronized, the time needed would be two times of the delay time of the subscriber in the worst case.

2) If the data stream selected for the subscriber is already active, then the time taken would be equal to the time delay of the subscriber.

Referring to Table 2.1 and 2.2, initially assuming all data streams as passive. For the subscriber S$_1$, system will chose data stream D$_6$. Therefore, S$_1$ will receive its first data point after twice its delay, i.e. 100 seconds. While when the subscriber S$_2$ processing data stream D$_6$ is already active and can satisfy its query, S$_2$ will receive first data point after 50 seconds.

Similarly at the time of the failure of current data stream, subscriber will receive next data points in the same manner as above. Table 2.3 shows the amount of time it took to choose a new data stream for a subscriber by varying number of data streams and the fixed number of subscribers.
Table 2.3: Time taken to choose a new data stream for a subscriber.

<table>
<thead>
<tr>
<th>Number of Data Streams</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time taken (ms)</td>
<td>25</td>
<td>26</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

2.5.3 DATA STREAMS OPTIMIZATION

In this experiment, we demonstrate that our system minimizes the number of active data stream while meeting the needs of all subscribers. Figure 2.7 shows the comparison with the basic system. In general, it is considered that for each subscriber a new data stream will be selected. Whereas in our system, using DQ aware catalogs and Metadata, the data stream which is already active is chosen and new delay and frequency interval is calculated to meet the need of the subscriber. If there is no active data stream which can accomplish that, we chose the data stream with the lowest frequency that satisfies the delay time from the list of data streams.

Looking at Table 2.1 and 2.2, and assuming that initially all providers are registered and passive. Figure 2.7 shows the number of providers that were activated when processing each subscriber. The active data stream at the end of processing all subscribers can be referred from the Table 2.4.

Table 2.4: Active data streams after processing all subscribers.

<table>
<thead>
<tr>
<th>Data Streams</th>
<th>D₂</th>
<th>D₆</th>
<th>D₈</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Int.</td>
<td>50</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>Delay Int.</td>
<td>100</td>
<td>200</td>
<td>80</td>
</tr>
</tbody>
</table>
2.5.4 NETWORK BANDWIDTH OPTIMIZATION

Here, we show that due to optimizations of data streams, autonomic computations of new delay and frequency interval, and decision to promote some query operations to the provider for the data streams, the DQS-Cloud system can reduce the number of data points transmitted from the provider to the server. We consider the bandwidth consumption of the network in terms of number of data points transmitted from the data streams to the server in the time interval of 1000 seconds. In a basic system, in the worst case, for ‘n’ subscribers, ‘n’ data streams will be selected. Therefore, the data points are transferred to each of the subscribers through their respective data streams. So the number of data points is the sum of all data points required by the subscriber.
Referring to Table 2.1 and 2.2 and Figure 2.8, it can be said, for the basic system if all 10 subscribers are active, then 370 data points are needed continuously in real time to the cloud server within 1000 seconds. Whereas in our system, the same data stream is used to meet need of many subscribers. Our system receive only 145 data points to meet the needs of these subscribers.

2.5.5 MEMORY AND CPU UTILIZATION

Here, it is shown that because of all the optimization we have incurred in our system, we have gained a significant performance in terms of CPU and memory utilization. We
compare our system against the basic system, which has DQ parameters but not the data quality aware techniques.

We generate synthetic data at the provider for each data stream, in order to replicate the real world scenario. The provider can receive data either from itself or from other sensor devices. This data is stored in the SQLite database. Therefore, for each sensor data stream, there are two corresponding process, first, to generate data points, and second, to interact with the cloud server.

For this experiment, all the data streams are running on a single provider, which is acting as a gateway, so we captured the CPU and memory utilization of the provider and the cloud server.

Despite of data quality aware techniques, memory utilization at the provider for both basic and DQS-cloud system came out to be same. Because of data streams and bandwidth optimization, cloud server uses less in-memory buffer storage with reduced database interaction and less processing power.

In terms of CPU utilization, for basic system, all data streams are considered as active, hence they continuously transmit the data as per DQ parameters. Whereas, in our system, only few data streams are active and some operators are pushed to the provider for each to reduce extraneous data points. CPU utilization is considerably low at both the provider and the cloud server. This is also due to the need of few data stream monitoring. Figure 2.9 and 2.10 shows CPU utilization at the provider and server, respectively.
Figure 2.9: CPU Utilization at provider

Figure 2.10: CPU utilization at cloud server
2.6 RELATED WORK

There has been considerable research work done in the area of wireless sensor network and stream processing engines that can be considered as predecessor to our work but not in true sense. Wireless sensor network (WSN) has a network of several sensors connected in a fashion that enables data to reach to the base station. Several research questions such as network formation, storage, in network processing, localization, debugging have been studies to the depth. However, WSN has not been designed to share the data across geographic region. An important contribution to make the sensor data available is undertaken by projects like IrisNet [10] and Sensor web [11]. These framework define a suite of web service interface and communication protocol to deliver the data to the consumer. Similarly, data stream processing engines and event processing engines such as Aurora [14], Borealis [13], StreamBase [31], and Esper [32] are also related to our projects. In this era of Internet, Internet of Things or Cloud of things is a novel paradigm which is rapidly gaining popularity in the world of wireless technology and sensor web. The basic idea all the things are connected and can communicate with the cloud. Xively [1] is an early attempt in this area which supports uploading and downloading of real time data using RESTful APIs. However, issues such as providing sensor data to internet scale as service, sensor feed discovery, sensor feed composition and interoperability are not adequately addressed. Also, they do not include the data quality aspect in the infrastructure for sensor Data as a service. We believe that DQS-Cloud is the first ever effort towards this direction which provides data quality aware real-time data marketplace cloud service.
2.7 CONCLUSION

It is expected that the Internet of Things paradigm will lead to servitization of the field of domain sensing. However, there is lack of effective infrastructure for supporting such servitization. This paper presented the design of DQS-Cloud, which is a novel cloud based framework for real-time sharing and discovery of sensor feeds. The concept of data quality (DQ) is central to the design of DQS-Cloud in the sense that it drives most key techniques of the framework. DQS-Cloud incorporates three unique features, namely a DQ aware sensor discovery techniques, a DQ aware technique for planning of feed processing workflows and a DQ aware fault tolerance mechanism. Our experiments show that the DQS framework is very effective in delivering appropriate sensor feeds to sensor data consumers while minimizing consumption of valuable resources such as bandwidth and CPU.
CHAPTER 3

SUMMARY

It is expected that the Internet of Things paradigm will lead to servitization of the field of domain sensing. However, there is lack of effective infrastructure for supporting such servitization. This paper presented the design of DQS-Cloud, which is a novel cloud based framework for real-time sharing and discovery of sensor feeds. The concept of data quality (DQ) is central to the design of DQS-Cloud in the sense that it drives most key techniques of the framework. DQS-Cloud incorporates three unique features, namely a DQ aware sensor discovery techniques, a DQ aware technique for planning of feed processing workflows and a DQ aware fault tolerance mechanism. Our experiments show that the DQS framework is very effective in delivering appropriate sensor feeds to sensor data consumers while minimizing consumption of valuable resources such as bandwidth and CPU.
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