DQS-Cloud: A Data Quality-Aware Autonomic Cloud for Sensor Services

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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.

I. Introduction

It is widely expected that the Internet of Things (IoT) paradigm will enable remote sensing on a massive scale. IoT will comprise of large numbers 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 the 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 II presents background and motivation on Internet of things and Data as a service. Section III explains the system architecture of our DQS-Cloud system. In section IV, we discuss three novel features of our system in detail. Section V demonstrates the experimental study of the system. In the next
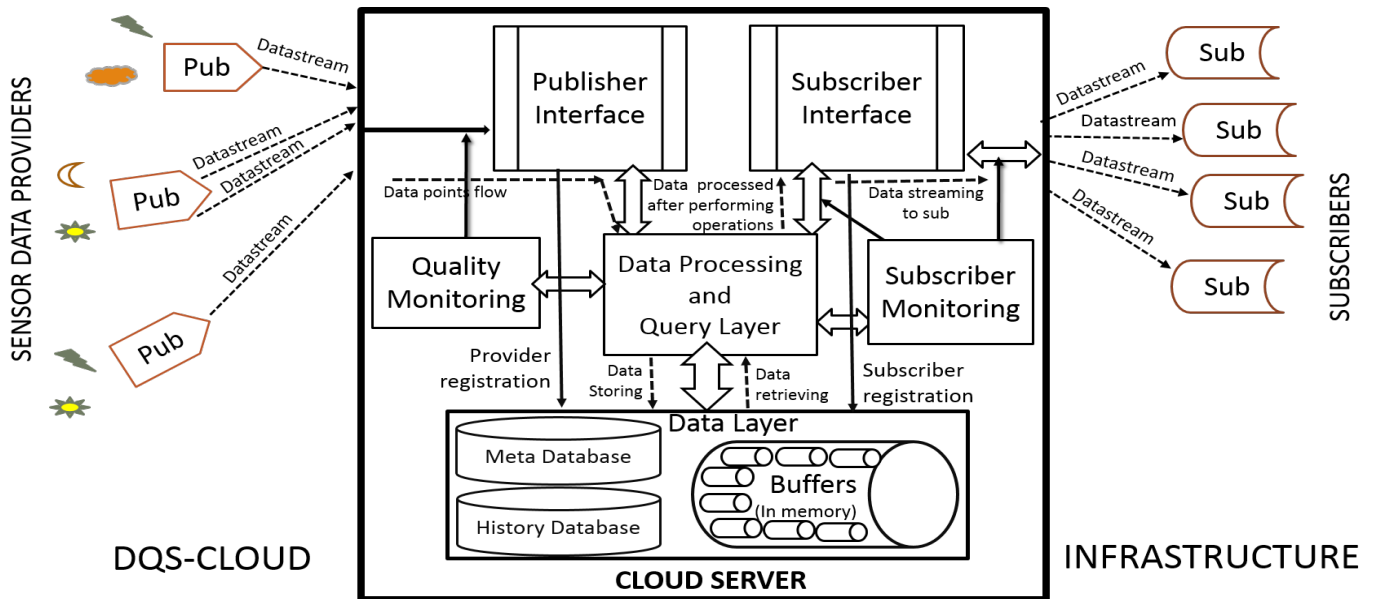
Fig. 1: High-Level System Architecture of DQS-Cloud

II. 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 [24], Azure marketplace [25] 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 systems 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.

III. 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 1 shows the high-level architecture of our proposed cloud system.

A. 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. To be a provider, a device must have the ability to send sensor data over the Internet. The second layer, *subscribers*, 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
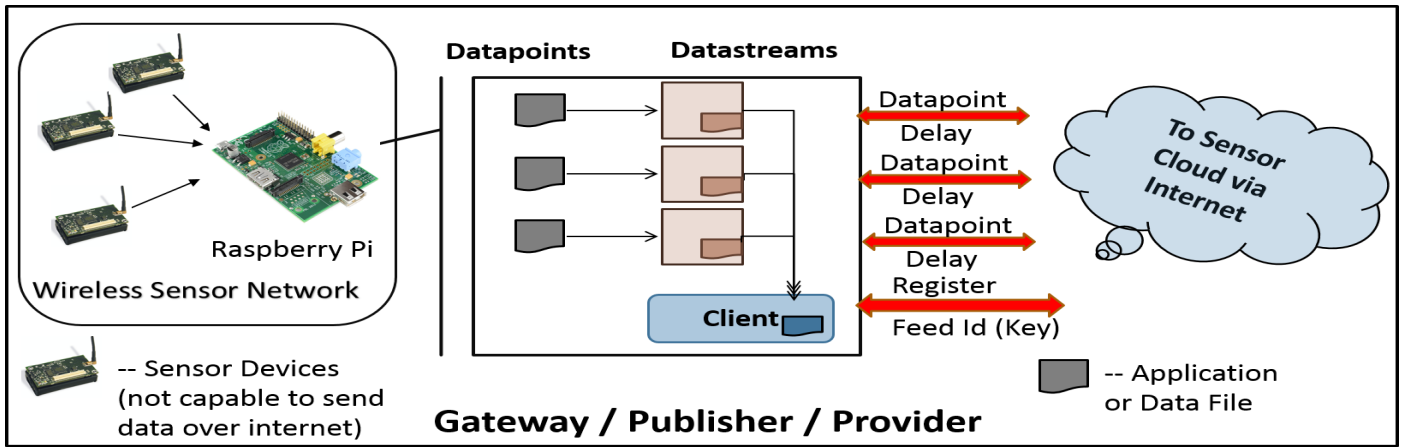
Fig. 2: High-Level Architecture of Provider

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 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 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.

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.

B. 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 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:

1) Effectively accommodate a diverse and possibly growing set of DQ attributes.
2) Quickly determine the feeds that satisfy the DQ requirements of particular domain applications or subscriber.
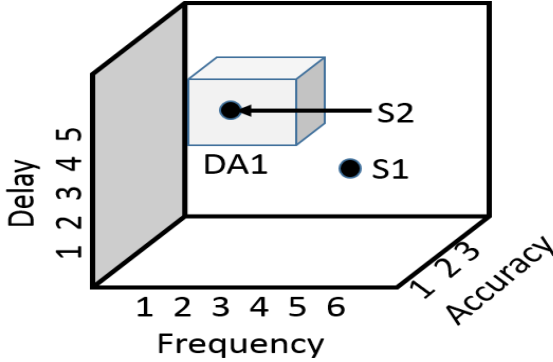3) Compare sensor feeds based on their DQ characteristics.

Fig. 3: Multidimensional DQ Model

C. 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, JSON 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.

1) Description of attributes - sensor type, latitude, longitude, etc.
2) 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 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.

IV. 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.

hostname	= 127.0.0.1
Port	= 5556
qDatastream	= temperature
qLatitude	= 33.955788
qlongitude	= -83.3823876
qAccuracy	= 3-5
qDelay	= 100000-240000
qFrequency	= 20000-60000

DatastreamId	= temperature
Unit	= Celsius
Accuracy	= 5
Frequency	= 50000
Delay	= 150000
Tags	= temperature, temp
Latitude	= 33.955788
Longitude	= -83.3823876

Subscriber Query   Publisher Description

Fig. 4: Query Representation

A. 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, 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.

We used two techniques to carry out the aforementioned limitations of other systems. First, without the subscribers intervention, our system incorporates automated technique for choosing an optimized data stream for the subscriber based on querys 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 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, for 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,
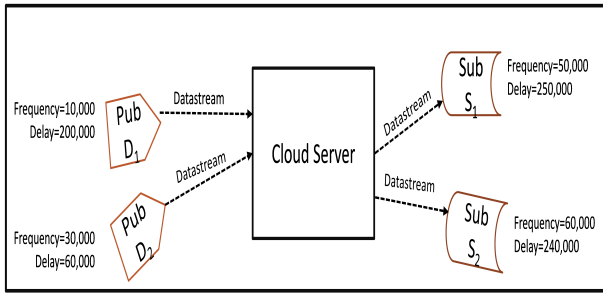
Fig. 5: Illustration of data quality aware service discovery and query planning.

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 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 V-C.

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.

B. 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:

$$S_i n = \frac{SubscriberDelay(S_i d)}{SubscriberFrequency(S_i f)}$$

Similarly, number of datapoints transferred per data stream of the provider is:

$$D_i n = \frac{DatastreamDelay(D_i d)}{DatastreamFrequency(D_i f)}$$

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, $D_i n$ must be greater or equal to $S_i n$, otherwise the data stream $D_i n$ cannot be selected for the subscriber. Thus, the number of data points to transmit will be more than the desired, i.e. $D_i n$, $D_j n$ 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 $S_i n$, $S_j n$ as needed. Therefore, we have reduced the number of data points from $\sum D_k n$ to $\sum S_k n$, where $k \in 1$ to m and m is number of subscribers. In Figure 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 IV-A, 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, $D_i d$ and $D_i f$ have new value equal to $\min(S_k d)$ and $\min(S_k f)$ where $k \in 1$ to m, respectively. With this approach, the data stream transmits $D_i n$ using new calculated values, which is less than or equal to $\sum S_k n$. In Figure 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 $D_i n$ data points, which is greater than or equal to $S_k n$, 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 requested 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 $S_i n$ and $S_j n$, respectively, from the cloud server. Therefore, we have reduced the number of data transmission from the cloud server to subscribers from $m D_i n$ to $\sum S_k n$, which is the desired number of data points. In Figure 5, the number of data points transferred to subscriber S_1 and S_2 is
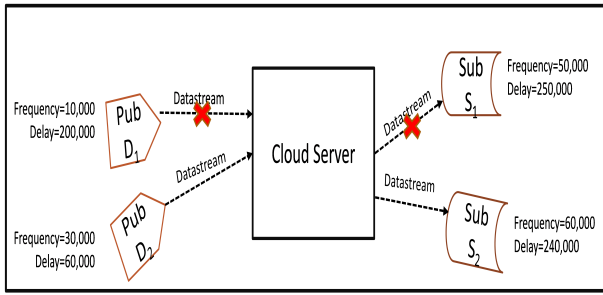
Fig. 6: Illustration of failure resilience and adaptations.

20 and 17, respectively.

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 V-D.

C. 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 such 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 providers 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.

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 6, as discussed for previous two features, D_1 is selected for both S_1 and S_2. The computed delay and frequency interval for D_1 is 50,000 milliseconds and 240,000 milliseconds, respectively. If data stream D_1 stops functioning properly and our system detects it, then for both subscriber S_1 and S_2 we need to choose a new data stream. As a result, our system chooses a data stream D_2 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 6, data stream D_1 is selected for both subscriber S_1 and S_2. The computed delay and frequency interval for D_1 is 50,000 milliseconds and 240,000 milliseconds, respectively. If subscriber S_1 stops functioning properly and our system detects it, then for data stream D_1 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.

V. EXPERIMENTS

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

1) The dynamic nature of the system.
2) Optimization incurred in terms of number of active data flows and bandwidth consumption.
3) 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

TABLE I: List of data streams considered for experiments.

Data Streams	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_10
Frequency Int.	50	25	30	50	60	10	40	30	45	35
Delay Int.	150	100	150	100	180	200	120	60	180	140

TABLE II: List of subscribers considered for experiments.

Subscriber	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_10
Frequency Int.	50	60	40	40	50	12	11	30	40	35
Delay Int.	250	240	200	200	100	240	330	90	80	140

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 in real time. To consider the network latencies we positioned publishers, subscribers and server geographically.

A. 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 I and II 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.

B. 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 I and II, 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. 500 seconds. While when the

TABLE III: Time taken to choose a new data stream for a subscriber.

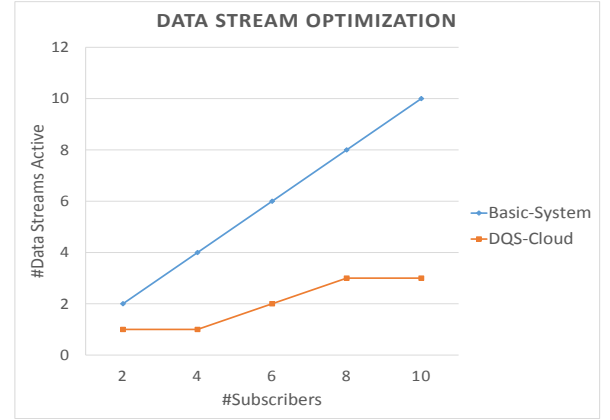| Num of Data Streams	2	5	10	50
Time taken (ms)	25	26	26	26

Fig. 7: Data Streams Optimization

subscriber S_2 processing data stream D_6 is already active and can satisfy its query, S_2 will receive first data point after 240 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 III 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.

C. 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 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 I and II, and assuming that initially all providers are registered and passive. Figure 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 IV.

TABLE IV: Active data stream after processing all subscribers.

Data Stream	D2	D6	D8
Frequency Int. Computed	50	11	30
Delay Int. Computed	100	200	80

D. 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.
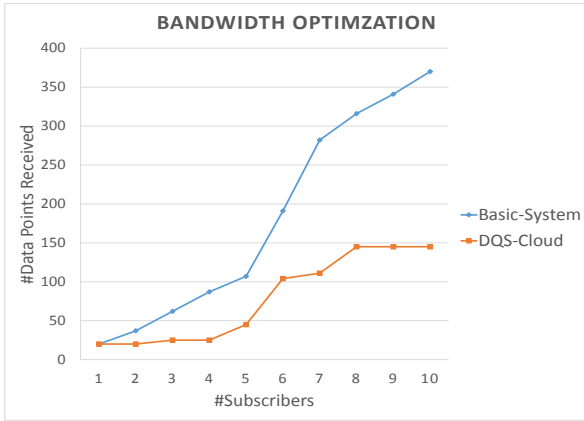

Fig. 8: Data Points Optimization

Referring to Table I and IIand Figure 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.

E. CPU and Memory 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.
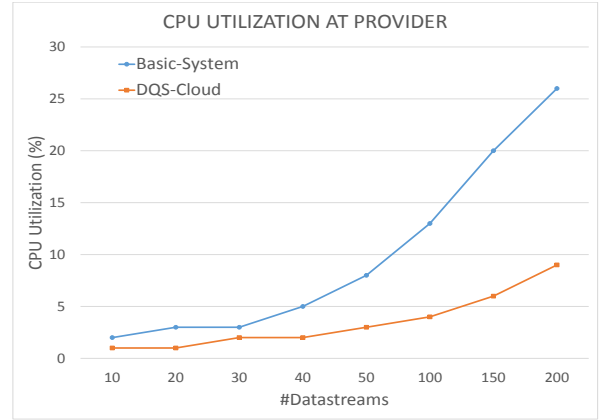

Fig. 9: CPU Utilization at provider

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 9 and 10 shows CPU utilization at the provider and server, respectively.
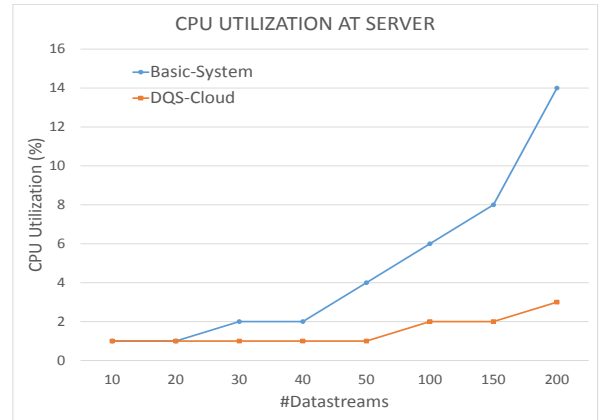

Fig. 10: CPU Utilization at Cloud server

VI. 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 [9] and Sensor web [10]. 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 [13], Borealis [12], StreamBase [26], Esper [27] 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.

VII. 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.

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