Capacity Planning of Aggregators and Multi-objective Optimization Approach to Optimal Data Transmission in Cloud Providers for Meteorological Sensor Network

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***Abstract*—To predict weather precisely, meteorologists need to collect and analyze meteorological data from wireless sensor devices installed in different areas. Today, cloud computing provides efficient storage and processing tasks for large-scaled sensor data. However, wireless sensors are constrained with bandwidth to transmit data to the cloud. Therefore, we propose a system model called cloud-based meteorological sensor network with aggregator approach which combines data from sensors and forwards to the cloud with better bandwidth. In this paper, the two main problems are considered for proposed system model. First, optimization approach to capacity planning of aggregators is addressed to obtain optimal number of aggregators for providing enough services to sensor data while reducing high investment. Second, optimal data transmission (ODT) algorithm based on multi-objective optimization approach is also proposed to minimize cost for provisioning resources and delay for transferring and processing when data from aggregators are allocated to multiple cloud providers. Then, the extensive numerical studies are performed for each problem. The numerical results provide not only optimal number of aggregators with the minimum total cost but also optimal data transmission from aggregators to the cloud with the minimum total cost and delay for the proposed system model.**

***Index Terms*—Cloud Computing, Capacity Planning of Aggregators, Multi-objective Optimization Approach, Wireless Sensor Network.**

I. Introduction

In recent years, wireless sensor networks have attracted a lot of attention by many researchers. A wireless sensor network (WSN) combines hundreds or even thousands of tiny and resource constrained sensor devices that are interconnected wirelessly and able to collect the data from surroundings [1]. WSNs have been employed in many applications such as transport monitoring, weather forecasting, military monitoring, agricultural monitoring, and healthcare monitoring. Among wide applications in WSN, weather forecasting has been played a critical part in people's lives to provide early warning for natural disasters such as landslides, water flooding, catastrophic earthquake, and volcanic eruption, etc. To predict weather precisely, meteorologists need to deploy a number of sensor nodes in different areas to periodically measure meteorological data such as temperature, humidity, wind speed, rainfall, atmospheric pressure, seismic wave, etc and transmit the data to the database server provided by meteorologists in order to process and report weather information to people. However, the volume of sensor data can be rapidly increased so that it will become big data in the future. As a result, the traditional database applications with limited capacity of storage and processing power cannot store and process such a large amount of data [2].

To resolve this issue, cloud computing is a potential solution which provides a plenty of storage and processing power resources without purchasing any hardware or physical infrastructure [3]. By applying cloud computing, a large amount of data from sensors can be stored and processed in an efficient manner. Then, the meteorologists can access the processed data from cloud providers and provide people with useful weather information. However, wireless sensor network has bandwidth constraint and could incur to network latency for the direct transmission of data to the cloud over remote distance [4].

To overcome this constraint, we propose a system model called cloud-based meteorological sensor network with aggregator approach. In the system, the aggregator approach provides aggregators which perform like buffering servers by collecting the data from wireless sensor network and forwarding to the cloud with faster bandwidth. With the use of aggregator approach, it can deal with bandwidth limitation occurred in sensors and improve the scalability of the proposed system.

The major contributions in this paper are presented below. First, optimization approach to capacity planning of aggregators for the proposed system model is addressed to determine the optimal number of aggregators with the minimum total cost. Second, optimal data transmission (ODT) algorithm based on multi-objective optimization approach is also proposed to allocate the data from aggregators to various commercial cloud providers with the minimum cost for resource provisioning and delay for transferring and processing. We also perform extensive numerical studies to evaluate the performance of proposed ODT algorithm. The results show that ODT algorithm can provide the optimal solution for transmitting data from aggregators to cloud providers while the total cost and delay is minimized.

II. Related Works

Recently, previous researchers have focused on wireless sensor network in various applications. A design level framework using WSN is proposed for developing smart environment by monitoring natural disasters [5]. Moreover, WSN system is deployed in agricultural field to monitor agricultural parameters such as air temperature, air humidity, soil temperature, soil water content and leaf wetness [6]. Besides, system architecture for smart healthcare based on WSN is proposed to provide remote health monitoring [7]. Furthermore, an intelligent transportation system based on WSN is illustrated for traffic monitoring and road safety management [8]. However, the aforementioned proposed systems transmit the data to the traditional database server and did not take into consideration the limitation of storage and processing capacities in database server. As a result, it can overload when the arrival of data from sensors is increasingly growing. Under overload, it may suffer excessive data loss and processing delay. Finally, it can seriously affect the timeliness of delivery of important information or results to users.

To deal with this issue, the development of cloud computing technology enables to store and process a large amount of data since it can offer abundant resources of storage and processing power. There are many research works benefit from cloud computing resources in different fields such as multimedia surveillance system, vehicular adhoc networks (VANET) technology, and smart environment monitoring as cited in [9], [10], and [11]. In this work, we apply the benefits of cloud computing resources for meteorological sensor network.

Although cloud computing can provide abundant storage and processing power resources, it is likely to occur serious network latency when wireless sensors with bandwidth constraint to transfer data to the cloud. To overcome this challenge, the concept of aggregator approach as buffer is introduced in some research works. A one-layer aggregation-based architecture is proposed in which aggregators are deployed to aggregate data from smart meters and send the aggregated data to relay nodes [12]. In patient monitoring, aggregator agent is applied to transmit the patient's parameters from body sensors to the cloud for storing and processing [13]. Similarly, typical wireless body area network (WBAN) architecture is proposed where body control unit is applied which serves as aggregator approach to collect the data from sensors and upload to remote server for remote continual healthcare monitoring [14].

Based on the works in [12], [13], and [14], this paper proposes a system model of cloud-based meteorological sensor network by exploiting aggregator approach. The aggregator approach can provide aggregators or buffers to reduce network latency for data transmission by bridging between sensors and cloud. In proposed system model, optimization approach to capacity planning of aggregators is applied to obtain the optimal number of aggregators with the minimum cost. Moreover, multi-objective optimization approach is also applied to achieve optimal data transmission from aggregators to the cloud with the minimum cost and delay.

To the best of knowledge, there are currently no works that address optimization approach to capacity planning of aggregators and multi-objective optimization approach to optimal data transmission in cloud providers in the field of wireless sensor network (WSN) especially for meteorological application.

II. Proposed System Model

In this section, the proposed system model of cloud-based meteorological sensor network is presented in Fig. 1.

This system model is mainly designed for one area where a set of several sensor devices are installed such as humidity sensor, temperature sensor, seismic sensor, vibration sensor, sound sensor, water sensor, etc. After deployment, all sensor nodes are fixed or stationary which can detect environmental data such as wind speed, wind direction, temperature, precipitation, soil moisture, barometric pressure, etc. A cluster head (CH) is then selected from other sensors based on higher computer power, storage space energy, and communication range criteria compared to others. Then, sensors can periodically send the data to CH via wireless direct connection using TDMA (Time

Division Multiple Access) protocols as it can prevent collision and retransmission of data [15]. The CH packages the data into the data packets and transmits the data packets per unit of time to the external aggregators via ZigBee network technology, which consumes very little energy, so that the lifetime of the sensor network can be improved. [16].

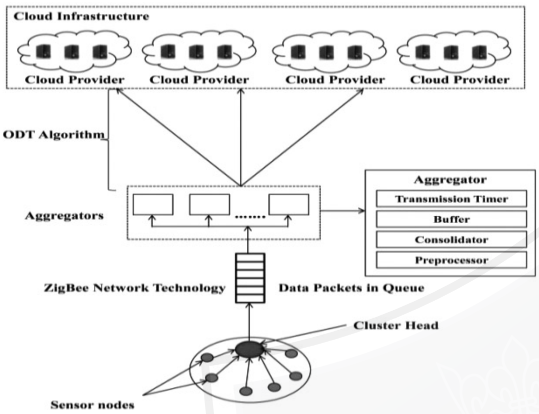

Fig. 1. System model of cloud-based meteorological sensor network.

After that, the aggregators collet the incoming data packets from sensors and perform step by step procedure. First, each aggregator preprocesses the data packets by eliminating erroneous and redundant data in order to improve accuracy level. Next, the processed data packets are aggregated as a single bucket by a consolidator to reduce the amount of data transmission and then stored in buffer. Then, a transmission timer in each aggregator transmits the consolidated data buckets from buffer to the cloud infrastructure by setting a specific time. Here, optimal data transmission (ODT) algorithm is implemented between aggregators and cloud infrastructure. In the cloud infrastructure, there are a number of cloud providers who offer different capacity of resources (i.e., storage, processing power, and network bandwidth) and also charge different prices for utilization of resources to consumers. Here, we need to pay attention that it can encounter higher cost for resource utilization and latency for transferring and processing when the aggregators randomly transfer data to cloud providers. To tackle this problem, the proposed ODT algorithm can make decision based on the optimal solution from multi-objective optimization approach to allocate data from aggregators to cloud providers with the minimum cost and delay.

Finally, the cloud infrastructure processes the data buckets from aggregators and produces the weather report including intensity, measurements, risk levels, maps, and images, etc. The warning system is also installed in the cloud to immediately alert meteorologists for disasters. Because of the alert, weather information can be noticed and transmitted to the public for disaster preparation.

IV. Problem Formulation

Since the proposed system model shown in Fig. 1 is designed by aggregators and cloud computing, we address and formulate the two main problems for capacity planning of aggregators to minimize total cost and optimal data transmission algorithm to minimize total cost and delay for data allocation from aggregators to the cloud.

A. Capacity Planning of Aggregators

First, the problem of capacity planning of aggregators is taken into account to be formulated. Since the aggregators are installed in the proposed system model, capacity planning of aggregators is an important issue for meteorologists that how many aggregators are required to handle the fast growing data from sensors while the investment of aggregators is minimized. More precisely, sensors continuously generate data so that it can be difficult to use only single aggregator for processing such exponential growth of data. Therefore, multiple aggregators need to be purchased from third party providers (e.g., Internet Service Providers (ISPs) or cloudlet providers [17]) to provide better system performance. However, applying multiple aggregators can lead to very high investment. Hence, it is important to determine the optimal number of aggregators in order to tradeoff between more aggregators for providing good service and fewer aggregators for reducing high investment.

To solve this issue, multi-server queuing theory is applied to formulate the problem for capacity planning of aggregators. Firstly, the nomenclatures are defined. It is assumed that the average arrival rate of data packets λ from cluster head to aggregators per unit of time is constant. In this case, data packets from cluster head to aggregators are queued based on the discipline of first-come-first-served (FCFS). The average service rate of data packets μ served by each aggregator per unit of time is also constant because it is assumed that the cluster head packages data packets to be the same size. Here, the service rate μ is higher than the arrival rate λ in order to become steady system. Let A denotes the number of aggregators. Let C_s denotes the service cost for purchasing and installing each aggregator. Let C_w denotes the waiting cost of each data packet in queue by assigning reasonable prices. In this case, the sum of these two costs must be minimized to obtain the optimal number of aggregators by trading off between providing higher service to reduce waiting time of data packets and lower service to reduce investment of aggregators.

According to the nomenclatures, we formulate the problem for capacity planning of aggregators using multi-server queuing theory below.

$$\text{Minimize: } C_{total} = AC_s + C_w\left[\frac{1}{(A-1)!}\left(\frac{\lambda}{\mu}\right)^A \frac{\mu\lambda}{(\mu A-\lambda)^2}\right]\left[\frac{1}{\left(\sum_{n=0}^{n=A-1}\frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n\right)+\frac{1}{A!}\left(\frac{\lambda^A}{\mu}\right)\left(\frac{A\mu}{A\mu-\lambda}\right)}\right]+\frac{\lambda}{\mu} \quad (1)$$

$$\text{Subject to: } \frac{1}{\lambda}\left\{\left[\frac{1}{(A-1)!}\left(\frac{\lambda}{\mu}\right)^A \frac{\mu\lambda}{(\mu A-\lambda)^2}\right]\left[\sum_{n=0}^{n=A-1}\frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n+\frac{1}{A!}\left(\frac{\lambda}{\mu}\right)^A\frac{A\mu}{A\mu-\lambda}\right]^{-1}+\frac{\lambda}{\mu}\right\}\le S_{max} \quad (2)$$

$$\frac{1}{\lambda}\left\{\left[\frac{1}{(A-1)!}\left(\frac{\lambda}{\mu}\right)^A \frac{\mu\lambda}{(\mu A-\lambda)^2}\right]\left[\sum_{n=0}^{n=A-1}\frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n+\frac{1}{A!}\left(\frac{\lambda}{\mu}\right)^A\frac{A\mu}{A\mu-\lambda}\right]^{-1}\right\}\le W_{max} \quad (3)$$

$$\frac{\lambda}{A\mu}<1 \quad (4)$$

$$A\in\{0,1,\ldots\} \quad (5)$$

The objective function in (1) shows minimizing the total cost including service cost and waiting cost for obtaining the optimal number of aggregators. In constraint (2), aggregators A serve the data packets in the system must not exceed the maximum service time threshold S_{max}. In constraint (3), the time taken of each data packet waiting in queue to serve by aggregators A must not exceed the maximum waiting time threshold W_{max}. In constraint (4), it controls that the usage of aggregators must be less than 1 in order to form a stable system. In constraint (5), decision variables are required to take integer values for the number of aggregators.

With the help of optimization approach, it can determine the optimal number of aggregators with the minimum total cost.

B. Optimal Data Transmission Algorithm

After knowing the optimal number of aggregators, the data buckets from each aggregator need to be transferred to cloud infrastructure for storing and processing. Since different cloud providers in infrastructure have different amount of resources and prices for resource utilization, it is a serious issue to choose cloud providers in order to minimize total cost for provisioning resources and delay for transferring and processing. In order to optimally transfer data buckets from aggregators to cloud providers with the minimum cost and delay, optimal data transmission (ODT) algorithm is developed by applying multi-objective optimization model which formulates the problem involving more than one objective function and enables to optimize simultaneously.

To formulate the multi-objective optimization model, the nomenclatures are first defined. Let $A=\{a_1,a_2,\ldots,a_{last}\}$ denotes a set of aggregators. Let n_a denotes the number of data buckets from each aggregator. Let $d_a^{(s)}$ denotes the size of each data bucket, $d_a^{(p)}$ denotes the processing power required by each data bucket, and $d_a^{(n)}$ denotes the network bandwidth required by each data bucket from each aggregator. Let $J=\{j_1,j_2,\ldots,j_{last}\}$ denotes a set of cloud providers. Let $t_j^{(s)}$ denotes the capacity of storage, $t_j^{(p)}$ denotes the processing power, and $t_j^{(n)}$ denotes the network bandwidth. Let $c_j^{(s)}$ denotes the unit cost for storage, $c_j^{(p)}$ denotes the unit cost for processing power, and $c_j^{(n)}$ denotes the unit cost for network bandwidth charged by each cloud provider. Let X_{aj} denotes the decision variable which indicates that aggregators a transfer data buckets to cloud providers j. Based on these nomenclatures, multi-objective optimization model is formulated as follow.

Minimize:

$$\sum_{a\in A}\sum_{j\in J}\left\{\left(c_j^{(s)}\times X_{aj}\right)+\left(c_j^{(p)}\times X_{aj}\right)+\left(c_j^{(n)}\times X_{aj}\right)\right\},\sum_{a\in A}\sum_{j\in J}\left\{\left(\frac{d_a^{(s)}\times X_{aj}}{t_j^{(n)}}\right)+\left(\frac{d_a^{(s)}\times X_{aj}}{t_j^{(p)}}\right)\right\} \quad (6)$$

$$\text{Subject to: } \sum_{j\in J}X_{aj}=n_a,\forall a\in A \quad (7)$$

$$\sum_{a\in A}\left(d_a^{(s)}\times X_{aj}\right)\le t_j^{(s)},\forall j\in J \quad (8)$$

$$\sum_{a\in A}\left(d_a^{(p)}\times X_{aj}\right)\le t_j^{(p)},\forall j\in J \quad (9)$$

$$\sum_{a\in A}\left(d_a^{(n)}\times X_{aj}\right)\le t_j^{(n)},\forall j\in J \quad (10)$$

$$X_{aj}\in\{0,1,\ldots\},\forall a\in A, j\in J \quad (11)$$

The formulation in (6) is multi-objective optimization to minimize total cost (for storage, processing power, and network bandwidth resources) and total delay (for data transmission and processing) for allocating data buckets from aggregators to cloud providers. The constraint in (7) ensures that the number of data buckets from aggregators is allocated to cloud providers. The constraints in (8)-(10) ensure that the resources of storage, processing power, and network bandwidth required by data buckets from all aggregators must not exceed the capacity of resources offered by each cloud provider. The last constraint in (11) specifies that the decision variable allocates non-negative integer number of data buckets from aggregators to cloud providers.

Using multi-objective optimization approach, the proposed ODT algorithm can minimize the total cost and delay for transferring data buckets from aggregators to cloud providers.

V. Parameter Setting And Numerical Studies

In this section, we define parameters and perform numerical studies for capacity planning of aggregators and optimal data transmission algorithm.

A. Capacity Planning of Aggregators

The average arrival rate of data packets λ is 160 data packets per hour from cluster head to aggregators. The average service rate of each aggregator μ can process 50 data packets per hour. The service cost C_s for purchasing and installing each aggregator is defined as \$10. The waiting cost of data packets in queue C_w is defined as \$15. In this case, an assumption is made that the waiting cost of data packets is higher than the service cost of aggregators to avoid the long delay in queue since the weather data is important in people's daily lives. The maximum service time threshold S_{max} is 300 sec per data packet while the maximum waiting time threshold W_{max} is 120 sec per data packet. The formulations in Section IV (A) can be solved on the basis of these parameters and the optimum number of aggregators can also be evaluated.

Fig. 2. shows the performance analysis of total cost, service cost, and waiting cost compared to the number of aggregators.

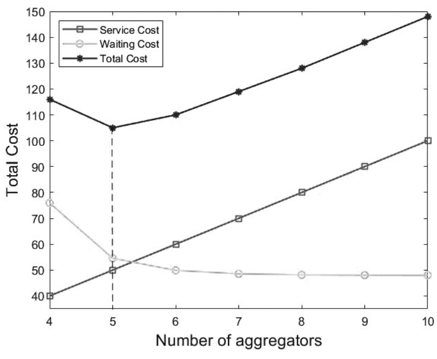

Fig. 2. Total cost compared to number of aggregators.

In Fig. 2, it is calculated using the formula $((\lambda / \mu)+1)$ to estimate the minimum number of aggregators (i.e., 4 aggregators) required for the system and then increased to 10 aggregators. As long as the number of aggregators is increased, the service cost is getting higher while the waiting cost is getter lower. It is clear to see that the optimal number of aggregators is 5 with the minimum total cost of \$105. At this optimal point, the waiting cost of data packets in the system is lessened compared to the level of 4 aggregators.

B. Optimal Data Transmission Algorithm

As we obtained the optimal number of five aggregators (i.e., $|A|$= 5) by using multi-server queuing theory, each aggregator needs to transfer data buckets to cloud providers for storage and processing. Suppose that there are different number of data buckets in each aggregator, e.g., na = $\{n_1 = 35, n_2 = 30, n_3 = 20, n_4 = 25, n_5 = 35\}$. The size of each data bucket from all aggregators is assumed as 20 (MB). Since the size of each data bucket is the same, the same processing power required by each data bucket from all aggregators is also assumed as 15 (CPU-hours) and the same network bandwidth required by each data bucket from all aggregators is also assumed as 6.9 (MB/sec).

In the proposed system model, we assume that the cloud infrastructure is composed of four cloud providers (i.e., $|J| = 4$). The storage capacity offered by cloud providers j_1 and j_3 are 1000 (GB), j_2 is 2000 (GB), and j_4 is 500 (GB), respectively. The processing power offered by cloud providers j_1 and j_4 are 1500 (CPU-hours), j_2 is 1200 (CPU-hours), and j_3 is 3000 (CPU-hours), respectively. For network bandwidth, all aggregators must share the bandwidth offered by each cloud provider. Cloud provider j_1 offers 375 (MB/sec), j_2 offers 500 (MB/sec), j_3 offers 625 (MB/sec), and j_4 offers 250 (MB/sec) to all aggregators a_1 to a_5. Cloud providers also define different prices for storage, processing power, and network bandwidth resources per each data bucket. For storage resource, cloud provider j_1 and j_3 charge \$0.70, j_2 charges \$0.80, and j_4 charges \$0.60, respectively. For processing power resource, cloud provider j_1 and j_4 charge \$0.50, j_2 charges \$0.40, and j_3 charges \$0.60, respectively. For network bandwidth resource, cloud provider j_1 charges \$0.25, j_2 charges \$0.30, j_3 charges \$0.35, and j_4 charges \$0.20, respectively. With these parameters, the multi-objective formulations in Section IV (B) can be solved and numerical studies are performed in the following subsections.

1. Weighted Sum Method

In order to solve multi-objective optimization problem, weighted sum method is applied. The general idea of this method is to associate each objective function with a weighting coefficient and minimize the weighted sum of each objective [18]. In this way, the original multi-objective problem is transformed into a single objective one and Pareto optimal solution can be obtained. Here, changing weights can provide different Pareto optimal solutions to decision maker. In this case, ODT algorithm is decision maker. Then, the ODT algorithm can choose the reasonable weights which provide the most preferred optimal solution among others. With weighted sum method, the form of multi-objective optimization in (6) is converted into single objective optimization as follow.

Minimize:

$$\sum_{a\in A}\sum_{j\in A}\left[w_1\left\{\left(c_j^{(s)}\times X_{aj}\right)+\left(c_j^{(p)}\times X_{aj}\right)+\left(c_j^{(n)}\times X_{aj}\right)\right\}+w_2\left\{\left(\frac{d_a^{(s)}\times X_{aj}}{t_j^{(n)}}\right)+\left(\frac{d_a^{(s)}\times X_{aj}}{t_j^{(p)}}\right)\right\}\right] \tag{12}$$

Subject to: (7), (8), (9), (10), (11)

TABLE I

SET OF PARETO OPTIMAL SOLUTIONS BY USING WEIGHTED SUM METHOD

Weights (w_1, w_2)		(-,1)	(0.1,0.9)	(0.2,0.8)	(0.3,0.7)	(0.4,0.6)	(0.5,0.5)	(0.6,0.4)	(0.7,0.3)	(0.8,0.2)	(0.9,0.1)	(1,-)
Pareto Optimal Solutions	$X_{a_1j_1}$	35	0	35	35	35	35	35	35	35	32	32
	$X_{a_1j_2}$	0	15	0	0	0	0	0	0	0	0	0
	$X_{a_1j_3}$	0	20	0	0	0	0	0	0	0	0	0
	$X_{a_1j_4}$	0	0	0	0	0	0	0	0	0	3	3
	$X_{a_2j_1}$	5	0	5	5	5	5	5	5	5	0	0
	$X_{a_2j_2}$	0	0	0	0	0	0	0	0	0	0	0
	$X_{a_2j_3}$	0	30	0	0	0	0	0	0	0	0	0
	$X_{a_2j_4}$	25	0	25	25	25	25	25	25	25	30	30
	$X_{a_3j_1}$	0	0	0	0	0	0	0	0	0	0	0
	$X_{a_3j_2}$	20	20	20	20	20	20	20	20	20	20	20
	$X_{a_3j_3}$	0	0	0	0	0	0	0	0	0	0	0
	$X_{a_3j_4}$	0	0	0	0	0	0	0	0	0	0	0
	$X_{a_4j_1}$	0	23	0	0	0	0	0	0	0	0	0
	$X_{a_4j_2}$	25	2	25	25	25	25	25	25	25	17	17
	$X_{a_4j_3}$	0	0	0	0	0	0	0	0	0	8	8
	$X_{a_4j_4}$	0	0	0	0	0	0	0	0	0	0	0
	$X_{a_5j_1}$	10	0	10	10	10	10	10	10	10	22	22
	$X_{a_5j_2}$	25	35	25	25	25	25	25	25	25	13	13
	$X_{a_5j_3}$	0	0	0	0	0	0	0	0	0	0	0
	$X_{a_5j_4}$	0	0	0	0	0	0	0	0	0	0	0
Total cost & delay		219.63	29.18	49.71	69.74	89.78	109.82	129.85	149.89	169.93	189.20	216.77

The objective function in (12) is formulated based on weighted sum method where w_1 defines the first weighting coefficient for total cost and w_2 defines second weighting coefficient for total delay. The constraints in (7) – (11) are addressed again. Then, GAMS/CPLEX solver [19] is applied to solve the formulations in (12), (7)-(11) and obtain a set of Pareto optimal solutions with different weights as given in Table I.

Since the objective function (the sum of total cost and total delay) in (12) is to be minimized, it is highlighted that the reasonable weights (w_1 = 0.1, w_2 = 0.9) yield the most preferred optimal solution with the minimum total cost and delay (i.e., 29.18). According to the optimal solution provided by weights (w_1 = 0.1, w_2 = 0.9), ODT algorithm can make decision that aggregator a_1 transmits 15 data buckets to cloud provider j_2 and 20 data buckets to cloud provider j_3, a_2 transmits 30 data buckets to cloud provider j_3, a_3 transmits 20 data buckets to cloud provider j_2, a_4 transmits 23 data buckets to cloud provider j_1 and 2 data buckets cloud provider j_2, and a_5 transmits 35 data buckets to cloud provider j_2.

2. Brute Force Search Algorithm

To evaluate the optimal solution provided by weights (w_1 = 0.1, w_2 = 0.9), brute force search algorithm is applied and numerical results are studied. The brute force search algorithm exhaustively finds every feasible solution until the optimal solution is found. Firstly, each possible solution is checked whether it is satisfied for all constraints or not. If the solution violates one constraint, it can be defined infeasible solution. Then, another possible solution is checked again. If the solution is satisfied for all constraints, it can be defined feasible solution and this solution is calculated into objective function. Then, different total cost and delay values will be obtained from different feasible solutions. Finally, the optimal solution can be chosen based on the objective either maximize or minimize. Table II shows the evaluation of optimal solution by brute force search algorithm.

TABLE II
EVALUATION OF OPTIMAL SOLUTION BY BRUTE FORCE SEARCH ALGORITHM

Decision Variables	Feasible Solutions				
$X_{a_1 j_1}$	0	35	15	20	20
$X_{a_1 j_2}$	15	0	0	0	0
$X_{a_1 j_3}$	20	0	0	0	0
$X_{a_1 j_4}$	0	0	20	15	15
$X_{a_2 j_1}$	0	5	0	0	0
$X_{a_2 j_2}$	0	0	0	0	0
$X_{a_2 j_3}$	30	25	25	25	30
$X_{a_2 j_4}$	0	0	5	5	0
$X_{a_3 j_1}$	0	0	0	0	0
$X_{a_3 j_2}$	20	20	20	10	20
$X_{a_3 j_3}$	0	0	0	10	0
$X_{a_3 j_4}$	0	0	0	0	0
$X_{a_4 j_1}$	23	0	0	0	0
$X_{a_4 j_2}$	2	25	25	25	25
$X_{a_4 j_3}$	0	0	0	0	0
$X_{a_4 j_4}$	0	0	0	0	0
$X_{a_5 j_1}$	0	10	10	10	0
$X_{a_5 j_2}$	35	25	25	25	25
$X_{a_5 j_3}$	0	0	0	0	0
$X_{a_5 j_4}$	0	0	0	0	10
Total cost & delay	29.18	29.32	29.54	29.48	29.51

In Table II, it is highlighted and proven the optimal solution which provides the minimum total cost and delay (i.e., 29.18) compared to the ones from other feasible solutions. In addition, this optimal solution is also similar to the one obtained by GAMS/CPLEX solver.

3. Sensitivity Analysis

Furthermore, sensitivity analysis is also performed to study how sensitive the optimal solution obtained by weights ($w_1 = 0.1$, $w_2 = 0.9$) by changing one input parameter while keeping other parameters constant. Table III shows the numerical results for sensitivity analysis.

In Table III, the parameters for size of data buckets, processing power of data buckets, bandwidth of data buckets, storage capacity of cloud providers, processing power capacity of cloud providers, bandwidth capacity of cloud providers, storage cost of cloud providers, processing power cost of cloud providers, bandwidth cost of cloud providers are changed and the numerical results are described. The results show that the optimal solution is not changed and stayed at optimal.

TABLE III

NUMERICAL RESULTS FOR SENSITIVITY ANALYSIS

Decision Variables	Size of data buckets	Processing power of data buckets	Bandwidth of data buckets	Storage capacity of cloud providers	Processing power capacity of cloud providers	Bandwidth capacity of cloud providers	Storage cost of cloud providers	Processing power cost of cloud providers	Bandwidth cost of cloud providers
	$a_1 = 19.9$ $a_2 = 19.9$ $a_3 = 19.9$ $a_4 = 19.9$ $a_5 = 19.9$	$a_1 = 16$ $a_2 = 16$ $a_3 = 16$ $a_4 = 16$ $a_5 = 16$	$a_1 = 6.91$ $a_2 = 6.91$ $a_3 = 6.91$ $a_4 = 6.91$ $a_5 = 6.91$	$j_1 = 1005$ $j_2 = 2005$ $j_3 = 1005$ $j_4 = 505$	$j_1 = 1510$ $j_2 = 1210$ $j_3 = 3010$ $j_4 = 1510$	$j_1 = 377$ $j_2 = 502$ $j_3 = 627$ $j_4 = 252$	$j_1 = 0.75$ $j_2 = 0.85$ $j_3 = 0.75$ $j_4 = 0.65$	$j_1 = 0.55$ $j_2 = 0.45$ $j_3 = 0.65$ $j_4 = 0.55$	$j_1 = 0.30$ $j_2 = 0.35$ $j_3 = 0.40$ $j_4 = 0.25$
$X_{a_1 j_1}$	0	0	0	0	0	0	0	0	0
$X_{a_1 j_2}$	15	15	15	15	15	15	15	15	15
$X_{a_1 j_3}$	20	20	20	20	20	20	20	20	20
$X_{a_1 j_4}$	0	0	0	0	0	0	0	0	0
$X_{a_2 j_1}$	0	0	0	0	0	0	0	0	0
$X_{a_2 j_2}$	0	0	0	0	0	0	0	0	0
$X_{a_2 j_3}$	30	30	30	30	30	30	30	30	30
$X_{a_2 j_4}$	0	0	0	0	0	0	0	0	0
$X_{a_3 j_1}$	0	0	0	0	0	0	0	0	0
$X_{a_3 j_2}$	20	20	20	20	20	20	20	20	20
$X_{a_3 j_3}$	0	0	0	0	0	0	0	0	0
$X_{a_3 j_4}$	0	0	0	0	0	0	0	0	0
$X_{a_4 j_1}$	23	23	23	23	23	23	23	23	23
$X_{a_4 j_2}$	2	2	2	2	2	2	2	2	2
$X_{a_4 j_3}$	0	0	0	0	0	0	0	0	0
$X_{a_4 j_4}$	0	0	0	0	0	0	0	0	0
$X_{a_5 j_1}$	0	0	0	0	0	0	0	0	0
$X_{a_5 j_2}$	35	35	35	35	35	35	35	35	35
$X_{a_5 j_3}$	0	0	0	0	0	0	0	0	0
$X_{a_5 j_4}$	0	0	0	0	0	0	0	0	0

4. Comparison with ODT Algorithm and without ODT Algorithm

In this subsection, the experiment is performed by varying the number of data buckets from each aggregator from 5 to 25 and comparing the result using ODT algorithm and without using ODT algorithm based on the weights ($w_1 = 0.1$, $w_2 = 0.9$) as depicted in Fig. 3.

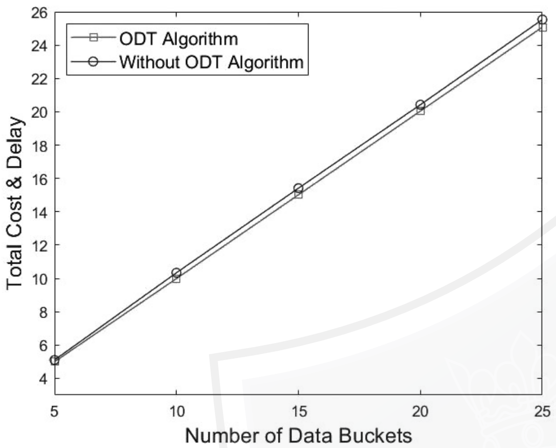

Fig. 3. Result comparison with ODT algorithm and without ODT algorithm.

As shown in Fig. 3, the result of using ODT algorithm is lower than that of without using ODT algorithm. Without using ODT algorithm, when the data buckets from aggregators are randomly transferred to cloud providers, it can incur to higher cost and latency. In contrast, since ODT algorithm applies multi-objective optimization, it is able to minimize total cost and delay for data allocation from aggregators to cloud providers.

VI. Conclusion

In this paper, we have proposed a system model of cloud-based meteorological sensor network in which aggregator approach is applied as an interface to alleviate bandwidth limitation for transmitting data from sensors to cloud. In proposed system model, optimization approach to capacity planning of aggregators is first presented. The result shows that using optimization approach can determine the optimal number of aggregators to meet the performance requirement for data from sensors while the investment is minimized. Moreover, Optimal Data Transmission (ODT) algorithm based on multi-objective optimization approach is also proposed to minimize cost and delay for data transmission between aggregators and cloud providers. Then, the proposed ODT algorithm has evaluated by numerical studies and experiments. According to the numerical results, ODT algorithm can optimally distribute the data buckets from aggregators among various cloud providers with the minimum cost and delay.

For the future work, we will consider the uncertainty of data arrival rate from sensor nodes and apply stochastic programming with two stages to minimize the total cost for capacity planning of aggregators.

References

[1] L. M. L. Oliveira, J. J. P. C. Rodrigues, A. G. F. Elias, and B. B. Zarpelão. (2014, Jan.). Ubiquitous monitoring solution for wireless sensor networks with push notifications and end-to-end connectivity. *Mobile Information Systems*. [Online]. *10(1)*, pp. 19-35. Available: https://content.iospress.com/journals/mobile-information-systems/10/1

[2] A. R. Syed, K. Gillela, and C. Venugopal. (2013, Jun.). The future revolution on big data. *International Journal of Advanced Research in Computer and Communication Engineering*. [Online]. *2(6)*, pp. 2446-2451. Available: https://www.ijarcce.com/upload/2013/june/44-Abdul%20Raheem-The%20Future%20Revolution%20on%20Big%20Data.pdf

[3] R. Buyya, C. S. Yeo, S. Venugopal, J. Broberg, and I. Brandic. (2009, Jun.). Cloud computing and emerging IT platforms: Vision, hype, and reality for delivering computing as the 5th utility. *Future Generation Computer Systems*. [Online]. *25(6)*, pp. 599-616. Available: https://www.sciencedirect.com/science/article/pii/S0167739X08001957

[4] B. Sheng, Q. Li, and W. Mao. (2010, Oct.). Optimize storage placement in sensor networks. *IEEE Transactions on Mobile Computing*. [Online]. *9(10)*, pp. 1437-1450. Available: http://www.cs.wm.edu/~liqun/paper/mobihoc06.pdf

[5] A.-S. K. Pathan, C. S. Hong, and H.-W. Lee, "Smartening the environment using wireless sensor networks in a developing country," in *Proc.* 8th International Conference Advanced Communication Technology, pp. 5-709.

[6] N. Shah, U. B. Desai, I. Das, S. N. Merchant, and S. S. Yadav. (2009, Jan.). In-field wireless sensor network (WSN) for estimating evapotranspiration and leaf wetness. *International Agricultural Engineering Journal*. [Online]. *18(3)*, pp. 43-51. Available: https://www.academia.edu/248698/IN-FIELD_WIRELESS_SENSOR_NETWORK_WSN_FOR_ESTIMATING_EVAPOTRANSPIRATION_AND_LEAF_WETNESS

[7] G. Virone, A. Wood, L. Selavo, Q. Cao, L Fang, T. Doan, Z. He, R. Stoleru, S. Lin, and J. A. Stankovic. (2006, Apr.). An advanced wireless sensor network for health monitoring. Presented at Transdisciplinary Conference on Distributed Diagnosis and Home Healthcare. [Online]. Available: https://pdfs.semanticscholar.org/3706/f2446de9ac8a466efdbdd8e0fd1f358631a5.pdf

[8] A. Pascale, M. Nicoli, F. Deflorio, B. D. Chiara, and U. Spagnolini. (2012, Mar.). Wireless sensor networks for traffic management and road safety. *IET Intelligent Transport Systems*. [Online]. *6(1)*, pp. 67-77. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.338.4514&rep=rep1&type=pdf

[9] M. A. Hossain. (2014, May.). Framework for a cloud-based multimedia surveillance system. *International Journal of Distributed Sensor Networks*. [Online]. *10*, pp. 1-12. Available: https://www.researchgate.net/publication/273610620_Framework_for_a_Cloud-Based_Multimedia_Surveillance_System

[10] F. Ahmad, M. Kazim, A. Adnane, and A. Awad. (2015, Dec.). Vehicular cloud networks: Architecture, applications and security issues. Presented at 8th IEEE/ACM International Conference on Utility and Cloud Computing. [Online]. Available: https://www.researchgate.net/publication/286624464_Vehicular_Cloud_Networks_Architecture_

Applications_and_Security_Issues

[11] M. Fazio, A. Celesti, A. Puliafito, and M. Villari, "Big data storage in the cloud for smart environment monitoring," in *Proc. Procedia CS*, 2015, pp. 500-506.

[12] A. Ghasempour and J. H. Gunther. (2016, Jan.), "Finding the optimal number of aggregators in machine-to-machine advanced metering infrastructure architecture of smart grid based on cost, delay, and energy consumption," in *Proc.* 13th IEEE Annual Consumer Communications and Networking Conference, CCNC, 2016, pp. 960-963.

[13] S. J. Devi, G. S. S. Devi, and G. M. T. Selvan. (2013, Dec.). Wireless sensor network integrating with cloud computing for patient monitoring. *International Journal of Engineering Sciences and Emerging Technologies (IJESET)*. [Online]. *6(3)*, pp. 316-323. Available: http://www.ijeset.com/media/0002/5N13-IJESET0603123-v6-iss3-316-323.pdf

[14] L. Hughes, X. Wang, and T. Chen. (2012, Nov.). A review of protocol implementations and energy efficient cross-layer design for wireless body area networks. *Sensors (Basel).* [Online]. *12(11)*, pp. 14730-14773. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3522938/

[15] T. Azizi, R. Beghdad, and M. Oussalah, "Bandwidth assignment in a cluster-based wireless sensor network," in *Proc. WCE*, 2013, pp. 1-6.

[16] Zigbee Setting Standards for Energy-Efficient Control Networks. [Online]. Available: https://www.yumpu.com/en/document/read/3733703/zigbee-setting-standards-for-energy-efficient-schneider-electric

[17] M. Satyanarayanan, P. Bahl, R. Caceres, and N. Davies, "The case for VM-based cloudlets in mobile computing," *IEEE Pervasive Computing*, vol. 8, no. 4, pp. 14-23, 2009.

[18] A. L. Jaimes, S. Z. Mart´ınez, and C. A. C. Coello, "An introduction to multiobjective optimization techniques," in *Optimization in Polymer Processing*, A. Gaspar-cunha and J. A. Covas, Ed. UK: Nova Science Pub Inc, 2009, ch. 1, pp. 29-57.

[19] GAMS Solvers. [Online]. Available: http://www.gams.com/help/index.jsp?topic=%2Fgams.doc%2Fsolvers%2Findex.html

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