A Node Replication Method to Guarantee Reachability for P2P Sensor Data Stream Delivery System on Heterogeneous Churn Situations

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Abstract—In this paper, we propose a method to construct scalable sensor data stream delivery system that guarantees the specified QoS of the delivery, i.e. total reachability to destinations even in a heterogeneous churn situation of the delivery server resources (nodes). There were some P2Pbased methods to construct scalable and efficient sensor data stream system that accommodates different delivery cycles by distributing communication loads of the nodes. However, existing methods could not guarantee the QoS of the delivery when the nodes on the system has heterogeneous churn rate. Our method extends existing method, which assigns the relay nodes based on the distributed hashing of the time-to-deliver, to decide the number of replication nodes according to the churn rate of each node and delivery paths. By simulations, we confirmed that our proposed method can guarantee the required reachability avoiding to increase unnecessary resource assignment costs.

Keywords-Sensor data, Data stream, Delivery cycle, Distributed processing, Replication, Churn resilience

I. INTRODUCTION

The Internet of Things (IoT) means that objects such as computing devices, electrical appliances and sensors connect to the Internet and interact each other to collaborate and realize various intelligent services. Especially sensors have an important role in the IoT, and the sensors generate observed data periodically. The continuous periodical data generated by the sensors is called 'sensor data stream.' In the IoT services, a huge amount of sensor data streams are required to deliveried to appropriate destinations such as users and processes. As for this sensor data stream delivery, the destinations are possible to require different delivery cycles for the same sensor data stream based on various reasons such as a performance of the receiver, network environments and applications. In the case where a live video of a solar eclipse taken from a camera is delivered, for example, the video is delivered at 30 fps to personal computer users connected to the Internet through a wire and is delivered at 10 fps to personal computer users connected to the Internet through a 3G channel while moving.

It is general in sensor data stream delivery that sensor data gained by one sensor is shared by a large number of users. Currently, various P2P-based techniques for dispersing the communication load of the deliverer (source) have been studied in the data streaming [1]–[6]. In these researches, in the case where the same sensor data stream is delivered to a number of terminals (destinations), the communication load of the source is dispersed by what the destinations send the received data to other destinations. When the delivery cycle is different, the sensor data stream whose delivery cycle is a common divisor of required cycles can be delivered to all of the destinations if the delivery cycles are in a multiple relationship or can be approximated as having a multiple relationship. However, the destinations receive redundant data which are not included to the times of each required cycle.

We have proposed P2P-based methods to construct scalable and efficient sensor data stream system that accommodates different delivery cycles by distributing communication loads of the nodes. In addition, we have also proposed a method that enhances the robustness of delivery system by replication of processing nodes [7]. However, the existing methods does not describe the suitable number of replication nodes and cannot guarantee the specified QoS of the delivery, i.e. total reachability to destinations when the delivery server resources (nodes) on the system has heterogeneous churn situations.

In this paper, we propose a method to construct scalable sensor data stream delivery system that guarantees the specified reachability as the QoS of the delivery even in heterogeneous churn situations of nodes. Our method extends existing method, which assigns the relay nodes based on the distributed hashing of the time-to-deliver, to decide the number of replication nodes according to the churn situation of each node and delivery paths.



Figure 1: System model

II. ADDRESSED PROBLEMS

A. Assumptions

In the sensor data stream delivery system that we assume in this paper, computers (nodes) to relay sensor data streams constructs P2P overlay network. The sensor data stream delivery system distributes the delivery loads to the nodes and keeps high scalability in an environment where there are a huge number of sensor data streams and destinations. Sensor data streams are periodically sent from their sources through the Internet and delivered to destinations by the hops among nodes. Destinations request sensor data streams with those delivery cycles to a specific node also through the Internet. We assume that selectable delivery cycles for each sensor data stream are given. Nodes are able to send sensor data to other nodes anytime, and sensor data are distributed for each sensor data stream and time.

The sensor data streams are S_i $(i = 1, \dots, l)$, destinations are D_i $(i = 1, \dots, m)$, and nodes are N_i $(i = 1, \dots, n)$. Figure 1 shows a model of delivery system. In Figure 1, the number of sensor data streams is l = 2, the number of destinations is m = 4 and the number of nodes is n = 3. The 'a' represents the sensor data stream S_1 , and the 'b' represents the sensor data stream S_2 . The delivery cycles are shown near sources, nodes and destinations in Figure 1. The 's' represents the source of sensor data stream, and the numbers near destinations are requested delivery cycles from each destination. In the case where the delivery cycle is 0, it means that the destination does not request the sensor data stream. This corresponds to case where a live camera acquires an image once every second, and D_1 does not view the image, D_2 and D_3 view the image once every second, and D_4 views the image once every three seconds, for example. In this paper, we assume that selectable delivery cycles for each sensor data stream are given and are represented by C_i $(i = 1, 2, \dots)$. The sensor data delivery system assigns delivery cycles or times to relay sensor data streams to nodes. The nodes send and receive various sensor data each other on specific times.



Figure 2: Assignment to a group of cycle

B. Replication of Assigned Nodes

Currently, we have proposed a P2P-based method assuming to delivery sensor data to a huge number of destinations with heterogeneous delivery cycles [7]. The proposed method determines relay nodes based on distributed hashing, and each node constructs delivery paths autonomously.

In the sensor data stream delivery, the number of data to send/receive varies among different delivery cycles. The shorter the delivery cycle is, the larger the number of data and the load are. Therefore, the existing method using distributed hashing first generates circular hash spaces for each sensor data stream and puts nodes on hash spaces based on the distributed hashing of the combination of sensor data stream and node ID. After that, the method divides each hash space into partial hash spaces as groups for each delivery cycle to make a partial hash space of the shorter cycle have the more nodes. The size of each partial hash space is determined based on its cycle. The method treats each partial hash space as circular and assigns related times for each cycle to nodes on its partial hash space. In the case where there are no nodes on the partial hash space, the method assigns the partial hash space to the nearest neighbor node on the next partial hash space. In addition, the method determines the root node on the partial hash space of the shortest cycle based on distributed hashing such as the least common multiple of cycles. The root node first receives data from the source of sensor data stream.

We have proposed a method that enhances the robustness of delivery system by a successor list used in Chord [7], [8]. Successors are nodes located next to the assigned node, and successor list is used for node and data replication. Figure 2 shows an example of the case where the number of nodes is n = 8, cycles are $C_i = i$ (i = 1, 2, 3), the size of a hash space is 2^p , and the length of the successor list is 2. In the existing method, the number of replication nodes is static to a specific value. However, real systems are probable to target a specific reliability as QoS, i.e. reachability to destinations. In this paper, we call the reliability "targeting system reliability" and assume to know the targeting system reliability at each time. SR_t ($0 \leq SR_t \leq 1$) denotes the targeting system reliability at time t. The appropriate number of replication nodes satisfying the targeting system reliability changes by cycle groups or times. If the number of replications is static, the cases that do not satisfy the targeting system reliability or increase unnecessary costs occur. In this paper, we aim to reduce the number of replication nodes satisfying the targeting reliability at each time.

III. NODE REPLICATION METHOD ON SENSOR DATA STREAM DELIVERY SYSTEM

In this paper, we propose a node replication method based on environmental variables such as targeting system reliability, the churn situations of each node and the number of destinations for each delivery cycle.

A. Idea

We assume that the delivery system can obtain the following elements, and each node determines own replication nodes at each time. Each node determines own replication nodes based on probabilistic calculations, and the expected value of the number of the reachable destinations satisfies the targeting system reliability.

• Targeting system reliability

In this paper, we define the reliability as the probability that sensor data reach the requesting destination or the rate of the reachable destinations per all requesting destinations. We assume that the provider of the delivery system determines the targeting system reliability to guarantee the quality of service. The number of replication nodes changes by the targeting system reliability. For example, if the targeting system reliability becomes higher, nodes send replicated data to more other nodes at each time to realize the targeting system reliability.

• Churn rates of each node

The churn situation of the original node and candidates of the replication nodes affect to the determined replication nodes. In this paper, we assume that each node knows own churn situation and the churn situations of the candidates of the replication nodes roughly. We call the churn situation "churn rate" and represent by the reliability of a node. $R \ (0 \le R \le 1)$ denotes the reliability of a node, and the churn rate is represented as 1-R. For example, if the candidates of the replication nodes have the low churn rates, the targeting system reliability can be achieved by a few replication nodes compared to the case of the high churn rates.

• The number of destinations for each delivery cycle The proposed method changes the degree of robustness enhancement for each delivery cycle based on the number of those destinations because the effect to enhance the robustness of nodes changes by the number of those destinations. For example, if the node assigned to the cycle group that has many destinations churns, the system reliability damages largely. Therefore, in this paper, we assume that nodes know the number of destinations for each cycle roughly, and nodes of the cycle group that has more destinations have higher robustness in the proposed method.

B. Determination of Replication Nodes

1) Non-Longest Cycle Group: In this paper, we call the group that has the longest cycle at each time "longest cycle at each time "non-longest cycle groups." R_0 ($0 \le R_0 \le 1$) denotes the reliability of the node assigned to time t in each cycle group, and R_u ($u = 1, 2, \dots, 0 \le R_u \le 1$) denotes reliabilities of candidates of its replication nodes in order. If the original node sends replicated data to v candidate nodes, the reliability of the cycle group at time t is calculated by $1 - \prod_{u=0}^{v} (1 - R_u)$. In the existing method using distributed hashing, the longest cycle groups. The reliabilities in the non-longest cycle groups need to achieve the reliability over SR_t because a churn in the longest cycle group is probable.

In the proposed method, the assigned nodes in the nonlongest cycle groups send replicated data to v candidate nodes at each time satisfying the following expression;

$$1 - \prod_{u=0}^{v} \left(1 - R_u\right) \ge \sqrt{SR_t} \tag{1}$$

2) Longest Cycle Group: C_i $(i = 1, 2, \dots, c)$ denotes selectable delivery cycles, and m_{it} $(i = 1, 2, \dots, c)$ denotes the number of destinations for each cycle group at time t. M_t denotes the number of destinations in the longest cycle group at time t, and the total number of destinations in the nonlongest cycle groups is calculated by $\sum_{i=1}^{c} m_{it} - M_t$. If the reliability of the non-longest cycle groups is approximately assumed to $\sqrt{SR_t}$, the expected value of the number of destinations in the non-longest cycle groups at time t, E_t , is calculated by the following expression;

$$E_t = \left(\sum_{i=1}^c m_{it} - M_t\right) \sqrt{SR_t} \tag{2}$$

Also in the case of the longest cycle group, R_0 denotes the reliability of the node assigned to time t, and R_u (u = 1, 2, ...) denotes reliabilities of candidates of its replication nodes in order. If the original node sends replicated data to vcandidate nodes, the reliability of the longest cycle group at time t is similar to the case of non-longest cycle groups and calculated by $1 - \prod_{u=0}^{v} (1 - R_u)$. If the assigned node in the longest cycle group has not churned at time t, the expected value of the number of destinations in the whole system is denoted by $M_t + E_t$. In the proposed method, the assigned node in the longest cycle group sends replicated data to v candidate nodes at each time satisfying the following expression;

$$\left(1 - \prod_{u=0}^{v} (1 - R_u)\right) \frac{M_t + E_t}{\sum_{i=1}^{c} m_{it}} \ge SR_t \tag{3}$$

IV. EVALUATION

In this paper, we evaluated the proposed method in Section III by simulation.

A. Simulation Environment

In the simulation environment, the number of nodes is $n = 2^7 = 128$, the number of sensor data streams is l = 1, and the number of destinations is m = 1000. The delivery cycles that destinations request are $C_i = i$ $(i = 1, \dots, 10)$ and determined at random between 1 and 10. In this environment, the maximum of the least common multiple of delivery cycles is 2520, and then the timetable for delivery is from time 0 to time 2519. The targeting system reliability is constant at all times and $SR_t = 0.9$ $(t = 0, 1, \dots, 2519)$.

In this simulation, we compare the proposed method with the methods that the number of replication nodes at all times is 0, 1, 2, 4 and 8. In addition, we compare with the method that determines the number of replication nodes at all times to satisfy the targeting system reliability based on the churn rates of nodes. Although the proposed method changes the number of replication nodes at each time, the comparative method uses the constant number of replication nodes at all times determined by the maximum value among all times. We call this comparative method "static method."

We calculated the number of replication nodes and the system reliability among the time of the least common multiple of selectable delivery cycles. The number of replication nodes relates to costs to keep robustness. We executed this simulation 10 times for each method and environments described later. We calculated the average of the results.

B. Number of Replication Nodes

Figure 3 and Figure 4 show the maximum instantaneous number of replication nodes for each cycle group and time by the churn rate of nodes. The Figure 3 shows the result in the case where the churn rate of nodes is constant to the value on the lateral axis. The Figure 4 shows the result in the case where the churn rate of nodes is individually determined at random between 0 and 1. The longitudinal axis shows the maximum number of replication nodes for each cycle group and time.

In this simulation environment, for example, in the case where the churn rate of all nodes is 0.1 in the constant scenario shown in the Figure 3, the maximum number of replication nodes in the unit time is 28. The higher the churn



Figure 3: The maximum of the number of instantaneous replication nodes on constant scenario



Figure 4: The maximum of the number of instantaneous replication nodes on random scenario

rate becomes, the larger the maximum number of replication nodes to satisfy the targeting system reliability becomes. In addition, the maximum number of replication nodes is the smallest in the random scenario shown in the Figure 4, and the larger the difference between churn rates becomes, the smaller the maximum number of replication nodes becomes.

Figure 5 and Figure 6 show the total number of replication nodes by the churn rate of nodes. The environment is same to the Figure 3 and Figure 4. The longitudinal axis shows the total number of replication nodes at time 0 to time 2519.

Similar to the results of the maximum number of replication nodes, the higher the churn rate becomes, the larger the total number of replication nodes becomes. In addition, the static method that determines replication nodes based on the churn rate shows similar results to the proposed method about the maximum number of replication nodes. However, the total number of replication nodes by the proposed method is smaller than the results by the static method especially in the Figure 6 because the proposed method changes the number of replication nodes each time based on situations such as the churn rate. In the environment where the churn rates of nodes are different, also the number of replication nodes to satisfy the targeting system reliability at each time is different. Therefore, the proposed method



Figure 5: Total number of instantaneous replication nodes on constant scenario



Figure 6: Total number of instantaneous replication nodes on random scenario

that changes the number of replication nodes at each time achieves to reduce costs caused by unnecessary replication nodes.

Figure 7 shows the cumulative relative frequency from time 0 to time 2519 against the number of instantaneous replication nodes in the unit time. The lateral axis shows the number of replication nodes in the unit time, and the longitudinal axis shows the cumulative relative frequency of times under the number of replication nodes shown on the lateral axis. The Figure 7 shows the maximum number of replication nodes at each time by the static method and the proposed method. The churn rates of nodes are determined at random between 0 and 1.

In the Figure 7, the maximum number of replication nodes in the static method is always 11. On the other hand, the maximum number of replication nodes in the proposed method is less than 4 at about 60% of the times. Moreover, the maximum number of replication nodes in the proposed method is less than 8 at the most times.

C. System Reliability

Figure 8 and Figure 9 show the minimum of the instantaneous system reliability. The instantaneous system reliability shows the rate of destinations at each time that receive data



Figure 7: Cumulative relative frequency of the number of instantaneous replication nodes



Figure 8: The minimum of the instantaneous system reliability on constant scenario

successfully. The Figure 8 shows the result in the case where the churn rate of nodes is constant to the value on the lateral axis. The Figure 9 shows the result in the case where the churn rate of nodes is individually determined at random between 0 and 1. The longitudinal axis shows the minimum of the instantaneous system reliability. Figure 10 and Figure 11 show the average of the instantaneous system reliability by the churn rate of nodes in the same environment. The longitudinal axis shows the average of the instantaneous system reliability.

In the Figure 8 and Figure 9, even the minimum of the system reliability satisfied the targeting system reliability, $SR_t = 0.9$, in the proposed method. Also the static method satisfied the targeting system reliability. However, the difference from the targeting system reliability is larger than the difference in the proposed method especially in the environment where the churn rates are different such as the Figure 9. Considering the results in the Figure 5 and Figure 6, the proposed method avoids to send replicated data to unnecessary nodes satisfying the targeting system reliability.



Figure 9: The minimum of the instantaneous system reliability on random scenario



Figure 10: The average of the instantaneous system reliability on constant scenario

V. CONCLUSION

In this paper, we propose a method to construct scalable sensor data stream delivery system that guarantees the specified QoS of the delivery, i.e. total reachability to destinations even in a heterogeneous churn situation of the delivery server resources. By simulations, we confirmed that our proposed method can guarantee the required reachability avoiding to increase unnecessary resource assignment costs.

In the future, we will study a technique to apply for the environment where the numbers of destinations for each delivery cycle are biased largely.

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Figure 11: The average of the instantaneous system reliability on random scenario

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