Dynamic resource control method based on real world representation with potential field

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***Abstract*—A real-world sensing application, which senses and analyzes the situation in the real world via sensor devices, has attracted increasing attention for providing new services to mobile users. In this paper, for targeting the application, we propose a highly adaptive resource control method that can control the amount of local computing resources, which is provided by the Mobile Edge Computing technology and the amount of network resources necessary for service provisioning. A basic idea is to express various information, such as the amount of sensor information and the amount of user access, into a simple potential field, and then update the potential field in a short cycle in a self-organized manner. Numerical results show that our resource control method based on the potential field is adaptive for the movement of users.**

***Index Terms*—Real-world Sensing, Mobile Edge Computing (MEC), Resource Virtualization and Control, Potential Field**

I. Introduction

The real-world sensing that analyzes real-world information around mobile devices is expected to provide more attractive services to users. Thanks to the development of mobile devices, various users enjoy network services through a constantly connected network. The recent mobile devices, such as the smartphone, is equipped with various kinds of sensors, which makes it possible to capture our real-world information. Some service providers acquire and analyze these sensor values of each user and to provide services such as indoor navigation [1] or crowd navigation [2].

One of important things in the real-world sensing is to understand the real world from a large amount of sensor information. For this purpose, data mining technologies for extracting real world information are being investigated [3]. However, as a matter of course, computing resources are required for applying data mining technologies, and it is currently considered to analyze and process information by aggregating the sensor information in data centers.

Recently, Mobile edge computing (MEC: Mobile Edge Computing) is under investigation in the networking research field. As its name indicates, MEC enables computing resources to be deployed at the edge, i.e., at the mobile-user side of the mobile network. In MEC, virtual machines are deployed on the mobile edge and they are used for application-specific computing resources [4]. MEC aims at reducing delay and improving immediacy by carrying out data processing at the mobile edge, not at the core or the data centers. Some applications such as video analysis and object tracking are already introduced [5]. Note that MEC architecture fundamentally follows NFV (Network Function Virtualization) architecture [4]. That is, virtual machines are deployed at the edge, and therefore applications can use the computing resources in a flexible manner.

The flexibility of computing resource deployment obtained by MEC is attractive for the real-world sensing. In the real-world sensing, the sensor information is spatially dependent data because the sensor information captures the real-world information of an environment. Thus, it is sufficient to analyze the spatially dependent data at the mobile edge rather than at the data center. Without MEC, the sensor information from mobile devices is sent to the data center (DC) via the edge router and the Internet. The sensor information is processed by using computing resources at the DC, and the processing result is sent back to the mobile devices. With this case, an analysis of the environment which surrounds mobile devices is performed by the data center that is usually located far from the mobile devices. The information exchange between the mobile devices and data centers degrades a delay characteristic of users response. Furthermore, because of the progress of cloud services and an increase of sensor devices, upstream information sent from users to DC is increasing, and it has been pointed out that unacceptable delays occur due to the aggregation of information in data centers [6], [7]. More importantly, the amount of sensor information is not constant, it always fluctuates depending on the user's movement and the events occurring around the mobile device. Therefore, it is desirable to deploy computing resources quickly based on the amount of the sensor information and to deploy network resources flexibly based on the value of the real-world information, i.e., amount of access requests to the results of data mining.

In this paper, we develop a dynamic resource control method that adjusts the amount of computing resources and network resource in conjunction with the change of events occurring in the real world. Specifically, the amount of sensor information in the real world and the amount of user access to this information are expressed as potential fields. The value of the potential is updated quickly in a self-organized manner, and then computing and network resources are placed based on the value of potential. With our potential expression and spatio-temporal interaction of potential, we achieve highly adaptive resource control against the change of the event occurring in the real world.

This paper is organized as follows. Section 2 describes a network resource control method based on real world expression using a potential field. In Section 3, we will examine the behavior of the potential field against the movement of the user and the behavior of the potential field under resource constraints. A conclusion of this paper and future work are described in Section 4.

II. A DYNAMIC RESOURCE CONTROL METHOD BASED ON REAL WORLD REPRESENTATION WITH POTENTIAL FIELD

A. Application scenario

We suppose following application scenario with the MEC architecture. Users have a mobile device, and sensor information of the real-world surrounding the mobile device is sent from the mobile device to the closest router. The router is the mobile edge and has computing resources for analyzing the sensor information. Hereafter, we call the router as the edge router. Using the computing resources of the edge router, sensor information is processed and analyzed at the edge router, and the result is stored at the edge router. For example, with the occurrence of a traffic accident, the sensor information around the point of the traffic accident is aggregated and analyzed at an edge router, and the result, e.g., the significance of the accident and/or degree of traffic congestion, is stored at the edge router. The results may be accessed by users which are close to the point of the traffic accident and by users spatially separated from the edge router through a network between the edge routers.

Thus, the computing resources of edge routers around the point of the traffic accident as well as network resource around the point of the traffic accident should be increased. More generally, the computing resource should be increased as the amount of sensor information increases, and the network resource should also be increased as the computing resource increases because the increase of sensor information will lead to giving more chance of accessing the information and/or retrieval of the information. This is why we consider three-layer potential field, which will be explained in the next section, to handle the real-world information.

B. Real world expression using potential field

A potential field is one of the approaches to express a state of control or control information itself. In the case of potential routing [8] which is used for controlling the route of information in the mobile ad-hoc and sensor network, the potential field expresses a distance to a sink node to which all the sensor node send their data. Each sensor node updates its potential in a self-organizing manner, and the potential of all nodes forms the potential field.

In this paper, we use the potential for expressing the amount of computing resources and network resources necessary in conjunction with the events occurring in the real world. With the simple expression by the potential, we realize a spatio-temporal resource control by updating and exchanging only the potential values without grasping details of real-world events and information accesses occurring in the real world.

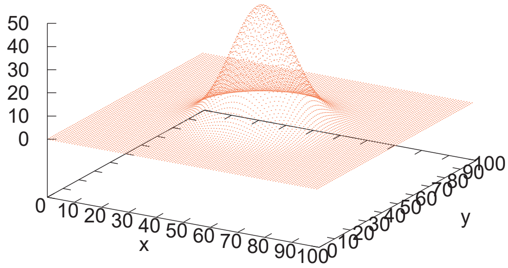


Fig. 1: The example of the potential field in ENV layer

Our method introduces three layers; ENV layer (Environmental layer), IR layer (Information Retrieval layer), and VoI layer (Value of Information layer). Each of three layers expresses some real-world information as potential and forms a potential field.

ENV layer expresses the amount of sensor information processed by each edge router, and IR layer expresses the amount of information retrieval offering access to the result of the information processing. VoI layer is most important layer in our method because it is designed such that a potential of VoI layer represents a potential access to an information. We will explain the detail of each layer in following.

1) ENV layer: A potential of ENV layer is defined as the number of users connected to an edge router or more directly the amount of sensor information at the edge router. Figure 1 illustrates an example of the potential field in ENV layer. In the figure, we suppose that some event such as a traffic accident occurs at the coordinate $(x, y) = (50, 50)$ on the two-dimensional space, and the amount of sensor information increases around the coordinate $(50, 50)$. Note that the increase of sensor information is not restricted to the coordinate $(50, 50)$, but may spread around the coordinate $(50, 50)$ due to the increase of a number of users caused by a traffic jam.

The potential of ENV layer is useful for preparing computing resource at the edge because more computing resource is necessary as more increase of the potential, i.e., the amount of sensor information. The actual computing resource should be determined by converting the potential of ENV layer with an appropriate function.

2) IR layer: A potential of IR layer is defined as the number of access requests to the information stored at an edge router. The potential represents the user's demand for the information and takes high value when the value of information of the edge router is high. When the value of information of the edge router is low, the potential takes low value.

3) VoI layer: A potential of VoI layer is defined as an amount of potential access to the information stored at an edge router. However, it is difficult to formally define the amount of potential access because the amount depends on the value of information and we do not have a formal method to define

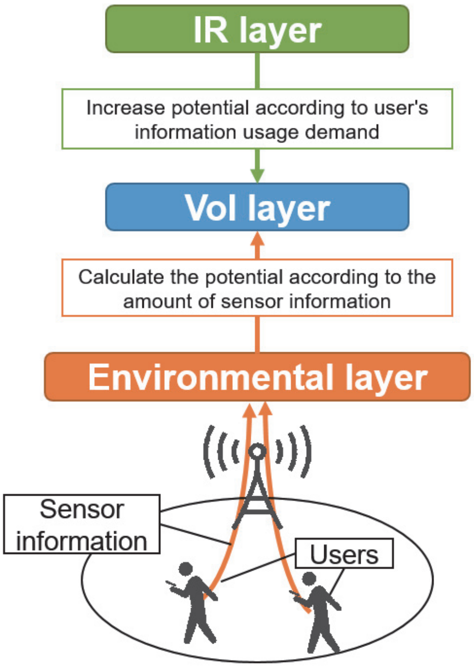


Fig. 2: Interactions among three layers

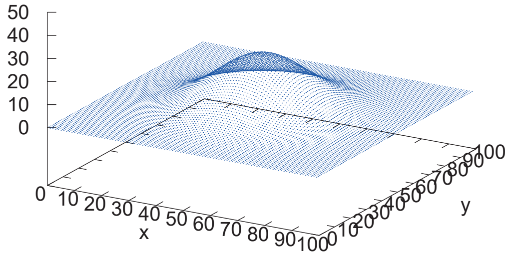


Fig. 3: Image of the potential field diffused in VoI layer

TABLE I: Explanation of each constant and parameter

x, y	Coordinate
t	Numbers of steps
$p(t, x, y)$	Amount of sensor information at step t at coordinate(x, y)
$C(t, x, y)$	Internal variable in VoI layer
$I(t, x, y)$	Potential in VoI layer
D_u	Diffusion coefficient of $C(t, x, y)$
D_t	The time constant of potential for $C(t, x, y)$
D_v	Diffusion coefficient of $I(t, x, y)$
n	Fixed decrease value of $I(t, x, y)$
G	Reduction coefficient of $C(t, x, y)$
P_f	Positive influence from ENV layer/IR layer
A_i	A set of adjacent nodes of node i

the value of information. Thus, we try to design a behavior of the potential such that the potential reflects potential access to the information.

Definitions of potentials of ENV layer and IR layer suggest that the potential of VoI layer should be increased (decreased) as the potential of ENV layer becomes high (low). That is, the potential of VoI layer should be determined based on the interactions between the potential of ENV layer/IR layer. This is because an increase of the amount of sensor information, that is, an increase of the potential of ENV layer reflects the occurrence of some event and leads to a potential access to the information. The potential of VoI layer should be also increased as the potential of IR layer increases because more access to the information reflects the value of information. Figure 2 illustrates the factors that affect the potential of VoI layer.

In addition to the interactions between ENV layer/IR layer, we should consider the spatio-temporal interactions of potentials at VoI layer when applications such as real-world sensing are targeted. Let us suppose that the potentials of ENV layer and IR layer are high at the edge router z at time t. A potential of VoI layer at z becomes high based on the interactions between ENV layer/IR layer. As for the spatio interaction, the potential of VoI layer should increase more because the information will be accessed not only from users connected to z but also from users connected to edge routers close to z. As for the temporal interaction, the value of information at time t is not lost immediately at time $t+1$ even when the amount of information access is lost and is decayed as the time passed. Such spatio-temporal interactions of the potential field are expressed by exchange and diffusion of potential values with neighboring edge routers, and its specific behavior of updating the potential is introduced at Section II-C. Figure 3 illustrates a potential field of VoI layer after when our equations of updating potential are applied for the potential field of ENV layer given in Figure 1. Compared with the potential field of ENV layer, we can see that the potential of VoI layer spreads widely because of a diffusion of the potential field.

C. Update potential

In this section, we explain the potential of VoI layer and equations with spatio-temporal interactions. Table I summarizes constants and variables used in the equations. $I(t, x, y)$, which is the potential of VoI layer located at (x, y) at time t, is calculated by the following equation,

$$\frac{\partial I(t,x,y)}{\partial t} = D_v\left(\frac{\partial I(t,x,y)}{\partial^2 x} + \frac{\partial I(t,x,y)}{\partial^2 y}\right) + P_f - n + D_c \tag{1}$$

The first term on the right side of equation 1 is the potential to be diffused from the adjacent edge routers. Hereafter, we call an edge router as a node for simplicity. The diffusion is based on the second derivative of the potential in each direction. This implies that we consider the differences of densities of potentials: the potential diffuses quickly when the density difference is large, or the potential diffuses slowly when the density difference is small. P_f is the influence from IR layer and n is a decay parameter. The last term, D_c is the influence from ENV layer which reflects the amount of sensor information and is defined as,

$$D_c = \begin{cases} D_t \frac{\partial C(t,x,y)}{\partial t} & (\frac{\partial C(t,x,y)}{\partial t} \geq 0) \\ D_t \frac{\partial C(t,x,y)}{\partial t} \tanh G \cdot I(t,x,y) & (\frac{\partial C(t,x,y)}{\partial t} < 0), \end{cases} \quad (2)$$

where

$$C(t+1,x,y) = (1-D_u)p(t,x,y) + \frac{1}{|A_i|} Du \sum_{j}^{A_i} C_j. \quad (3)$$

$C(t,x,y)$ is an internal variable in VoI layer and is calculated based on sensor information amount p. $C(t,x,y)$ reflects the change of amount of the sensor information not only at the node (x,y) but also the adjacent nodes $(x\pm1,y),(x,y\pm1)$. When the diffusion coefficient D_u is large, the amount of sensor information at adjacent nodes is reflected more.

In equation 2, when the derivative of $C(t,x,y)$ is negative, it is multiplied by $\tanh G \cdot I(t,x,y)$. This is to prevent $I(t,x,y)$ from becoming negative values when the value of $I(t,x,y)$ is close to 0.

D. Resource control based on a potential update formula considering resource constraints

In the previous section, we have designed the potential of VoI layer such that it reflects the potential access to an information stored at (x,y) through influences from ENV layer/IR layer and spatio-temporal interactions in VoI layer. Since the potential of VoI layer expresses the potential access to the information, the amount of the network resources should be prepared based on the potential field of VoI layer. However, since an amount of network resources are finite in general, it is necessary to modify equations for updating a potential with consideration of resource constraints.

Here, we suppose that network resources cannot be added anymore against the increase of information access to a node due to the resource constraints. In this case, the information access to the node should be relaxed by accommodating the part of the access at the other nodes. Considering the application such as real world sensing and MEC applications, it is desirable to compensate for the insufficient resource at a node by increasing the resource allocation at adjacent nodes which are spatially close to the node. Given a threshold of the potential value which corresponds to the limit of resources, the diffusion coefficient of the potential, D_v, is modified to,

$$D_v = \begin{cases} D_1 & (When \text{ I(t,x,y)} < the\ threshold\ value) \\ D_2 & (When \text{ I(t,x,y)} \geqq the\ threshold\ value). \end{cases} \quad (4)$$

D_1 is the diffusion coefficient under the condition that the potential is less than the threshold value and we do not have to deal with resource constraints, D_2 is used for the situation that the resource constraints are crucial. When a potential of a node reaches or exceeds the threshold value, diffusion of the potential should be accelerated. We, therefore, use D_2 which is greater than D_1 as the diffusion coefficient under the resource constraints. With the diffusion coefficient D_2, the potential of the node decrease more and the potential of the adjacent nodes increases more. After updating the potential considering resource constraints based on the above-mentioned equation, resource allocation is performed based on the potential of each node.

TABLE II: Parameter configuration

D_u	0.6
D_t	0.6
n	0.0001
G	0.6

In the case where there is a large discrepancy between the potential value of VoI layer and the amount of resources that can actually be allocated, it is necessary to reduce the amount of sensor information. For this purpose, the potential of VoI layer should be used as an influence to control the potential of ENV layer and/or IR layer. The mutual interactions between layers must be considered, but this is our future subject.

III. SIMULATION

In this section, we examine the behavior of the potential field of VoI layer by updating the potential with equations in Section II-C. The purpose of simulations is to confirm that the potential field of VoI layer can follow the fluctuation of the potential field of ENV layer and that the potential of nodes reflects the limitation of network resources. Thus, influence from the potential field of IR layer, P_f is set to 0 and is not considered hereafter. The values of the parameters used in our simulation are summarized in Table II. We examined two network scenario. At the first scenario, we consider the square lattice network where edge routers are placed at the bond of the lattice and they are connected through links. At the second scenario, we use the actual traffic data from PeMS system. Edge routers are assumed to be placed at measurement points of the PeMS system for the second scenario.

A. Results of the first scenario

We use a network where edge routers are connected in a grid of 100×100. Edge routers are equally spaced and each edge router exchanges information of its own potential value and diffusion coefficient $D_v(D_1 or D_2)$ with four neighboring edge routers at each step. The potential field of ENV layer is supposed to reflect the amount of sensor information generated by mobile devices, and the potential field will be changed based on the movement of users. As for the model of the user movement, we consider a simple model in which a group of users moves along either x-axis or y-axis with fixed velocity, which we suppose an orthogonal transport network of Osaka in Japan. More specifically, the potential of ENV layer $p(t,x,y)$ of node (x,y) at a step t is set to,

$$\begin{aligned} p(t,x,y) = {} & \alpha_1 \exp(-\frac{(y-50)^2}{\gamma_1}) \sin(\frac{t}{100}\beta_1 + \frac{x}{10}) \\ & + \alpha_2 \exp(\frac{(x-30)^2}{\gamma_2}) \sin(\frac{t}{100}\beta_2 + \frac{y}{10}) \\ & + \alpha_1 + \alpha_2. \end{aligned} \quad (5)$$

With this equation, the group of users that moves along the x axis and the group of users that moves along the y axis direction are moves with a fixed velocity, and these two groups

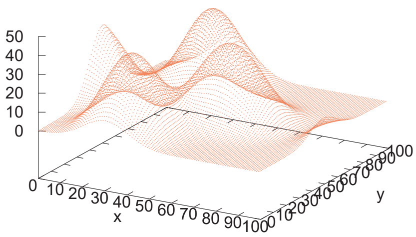


Fig. 4: The example of the potential field in ENV layer of equation 5

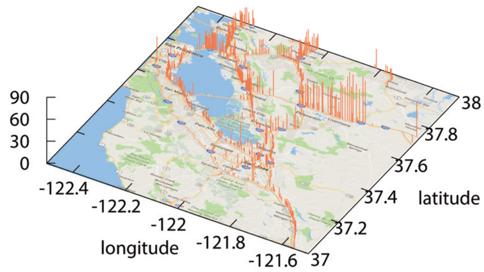


Fig. 5: The example of flow obtained from PeMS

intersect at the coordinates $(x, y) = (30, 50)$. Note that α, β and γ are parameters that adjust the maximum value of potential in each axis direction and degree of changes of number of users. In this paper, we set $\alpha_1 = \alpha_2 = 20$, $\beta_1 = 1$, $\beta_2 = 0.4$, $\gamma_1 = \gamma_2 = 200$. Fig.4 shows an initial settings of the potential field of ENV layer.

We examined the behavior of potential $I(t, x, y)$ under resource constraints. The diffusion coefficient defined in Equation 4 is used for this simulation. Fig.6 shows the potential $I(t, 30, 50)$ and the potential $I(t, 30, 51)$, where D_1 is 0.01 and D_2 is 0.025. The threshold value of the potential is set to 50. Each figure of Fig.6 shows the potentials $p(t, 30, 50)$ and $p(t, 30, 51)$ of ENV layer, and the potential without a potential constraint is depicted as I (non-constraint) for reference purpose. Looking around step 2200 of Fig.6, when the potential reaches the upper limit at coordinates $(x, y) = (30, 50)$, $I(t, 30, 50)$ is not exceed the threshold value. This is because the potential diffuses to the adjacent nodes, and we actually observe that the potential $I(t, 30, 51)$ is larger than the potential with no resource constraint.

B. Results of the second scenario

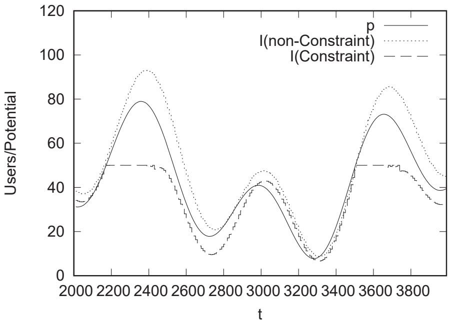
The second scenario uses the data collected by Performance and Measurement System (PeMS) which is a system that gathers traffic information of freeway in California. In PeMS, stations are installed at various points on the freeway, and each station is assigned an ID as an identifier. In addition, information such as amount of traffic flow is collected from each station every 30 seconds. In this paper, we regard these stations as edge routers, and calculate the potential for each station. The data from PeMS system includes metadata indicating station ID, longitude, latitude, and freeway number, and a RAW data showing station ID and amount of traffic flow. Thus, a time-series data of amount of traffic flow at each coordinate can be obtained. Figure 5 shows the integration of the flow graph obtained from the stations around San Jose. An geographical map is also inserted in the figure. The distance between actual stations is also calculated and we set 200 m as a unit of distance in the figure. Note that when the distance between stations is less than 1 unit, a data from either of stations is ignored. Also, adjacent stations on the same freeway are assumed to be connected though the actual connectivity of stations may be different. Each station exchanges information of its own potential value and diffusion coefficient $D_v(D_1, D_2)$ with the adjacent station every fixed step and one step is set to 30 seconds.

Using the actual data obtained from PeMS, we examine the behavior of the potential under resource constraints. There are many stations in PeMS, so we select three stations that are placed in the same freeway. Their ID is 401948, 401937, 401936, and denote three stations as A, B and C respectively. Station A is located in between stations B and C. Figure 7 shows the amount of flow of the vehicle and the potential when there is resource constraint and nothing where D_1 is 0.01 and D_2 is 0.2. The threshold value of the potential at station A is set to 40, and there is no resource restriction at station B and C. Looking at step 800 in this figure, we observe that the increase in potential of station A is suppressed near the threshold value as a result of setting higher diffusion coefficient. We also observe that the potentials are increased at stations B and C, and the ascending value of station B is much larger than station C. This is because the distance between station A and station B is smaller than the distance between station A and station C. For updating the potential, we change the amount of diffusion dependent on the distance between nodes; the smaller the distance between the nodes is, the larger the amount of diffusion is set in this paper. When a network topology in which distances between stations are remarkably different, there is a possibility that the fluctuation of the potential may not match the fluctuation of the real world. Modifications of equations may necessary to handle the distance between stations, but it is left for our future work.

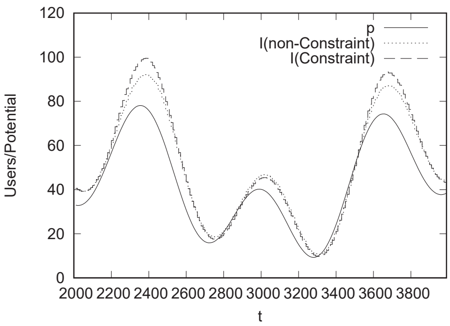
From the above, we confirm that the potential of VoI layer is changed immediately when the amount of the sensor information are changed. We also confirmed that under the resource constraint, the potential of adjacent nodes is further increased.

IV. Conclusion

From a viewpoint to improve the quality of experience, it is important to adjust computing resources and network resources in accordance with changes in the real world situation in applications requiring information processing. In this paper,

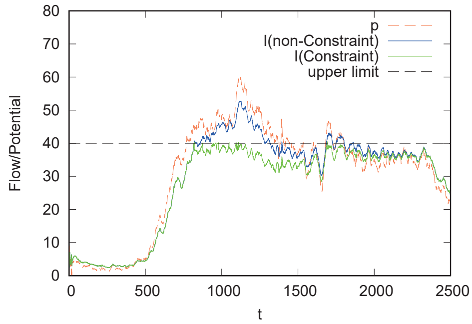


(a) $(x, y) = (30, 50)$

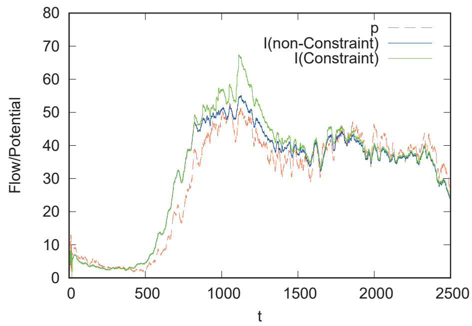


(b) $(x, y) = (30, 51)$

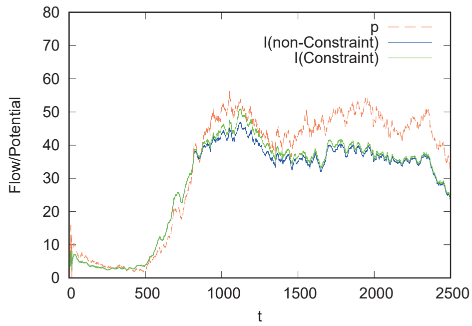
Fig. 6: Transition of $I(t, x, y)$:where $D_1 = 0.01, D_2 = 0.025$



(a) station A(ID=401948)



(b) station B(ID=401937)



(c) station C(ID=401936)

Fig. 7: Transition of $I(t)$ on each station:where $D_1 = 0.01, D_2 = 0.2$

we propose a dynamic resource control method that expresses the amount of sensor information and user access to real world information as a potential field, and allocates a resource amount according to the potential value. The proposed method instantly reflects changes in events occurring in the real world. Furthermore, by incorporating self-organizing spatiotemporal diffusion of potential, we allocate resources to prepare for event fluctuations and potential information access.

In this paper, we confirmed that the potential field formation and resource constraint are considered by using computer environment. In the future, we will evaluate the influence among the layers and evaluate the influence of the values of various parameters including the diffusion coefficient on the immediacy of the potential field and the ability to cope with environmental change.

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