Principle of Autonomous Decentralized Flow Control and Layered Structure of Network Control with Respect to Time Scales

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1 Introduction

Network control mechanisms in networks can be categorized by the time scales on which an individual control takes effect and they form a layered structure with respect to the time scales. In high-speed networks, the processing speed of each node is high but the propagation delay is the same as in slower networks, because it is constrained by the speed of light. So, the framework of network control on a short time scale should be an autonomous decentralized system [1]. We have proposed an autonomous decentralized flow control mechanism applicable to high-speed networks [2], and have investigated its stability and adaptability to dynamic network state [3]. In this article, to clarify the aim of our flow control mechanism, we show supplemental explanations from the following three points of view:

- Layered structure of network control with respect to time scale and the inevitability of autonomous decentralized control on a short time scale.
- The relationship between local decision making at a node and the performance of the whole network, in order to achieve high global performance as a micro-macro link.
- The principle of our flow control derived from the efficient framework of parallel computing as an actual approach to realize appropriate global performance by controlling local decision making.

2 Layered Structure of Network Control and Time Sensitive Control in High-Speed Networks

Every packet in a network is either in a node or on a link. In high-speed networks, many packets are on links compared with in nodes. Since the packets currently stored in nodes are not being transmitted over the network, it is necessary to maximize the number of packets on links in order to realize high performance of the whole network. However, the only packets we can control are those stored in nodes. Thus, higher performance of the whole network involves many uncontrollable packets being propagated on links. Therefore, inappropriate flow control cannot produce a state that has high performance and stability.

Individual control mechanisms work well on their appropriate time scales and they cooperate with each other. For example, increasing the link capacity and routing fall on the long and medium time scales, respectively. Window flow control such as TCP acts on the time scale of the round-trip delay. In high-speed networks, since a lot of packets are being propagated on links, control delay greatly affects on the performance. The centralized control cannot collect information about the whole network immediately. Since time-sensitive control must take effect immediately, its framework is inevitably an autonomous decentralized system.

Figure 1 shows a sequence of human behavior as an analogy. When an accident occurs, we immediately act. This action is time-sensitive and is achieved by a spinal reflex. After that, essential treatment is performed through cerebration on a relatively long time scale. The aim of our control [2, 3] is to take immediate effect by autonomous decentralized control. The centralized control is effective on relatively long time scales and is compatible with our control in the layered structure.

3 Micro-Macro Link in the Framework of Autonomous Decentralized Flow Control

There are phenomena in nature where local interactions on the micro scale produce symmetry on the macro scale. For example, local interactions among water molecules lead to highly symmetrical snow flakes. By applying this mechanism, although time-sensitive control on a short time scale can not use global information about the network, we may be able to control the global performance through local decision making at the nodes. This framework is not always

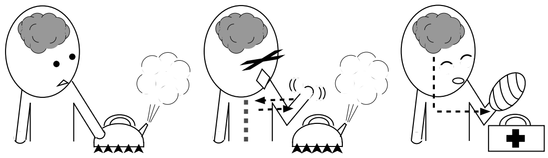

Figure 1. Layered structure of behaviors with respect to time scales

required to work effectively on a long time scale, but it should be effective until control on a longer time scales takes effect.

In the framework of our control [2, 3], we desire that global performance is indirectly controlled immediately by the predefined rule for local decision making at nodes. Nodes at distant locations do not communicate with each other. So, in spite of the constraint of light speed, appropriate global performance is achieved quickly. Since the centralized control cannot achieve the performance quickly due to the constraint of light speed, our control seems to take effect faster than the speed of light.

4 Principle of Autonomous Decentralized Flow Control

The actual way of achieving our control mechanism is similar to parallel computing. A typical case where parallel computing is effective is solving temporal evolution equations of a wave or fluid which are based on local interaction, *e.g.*, the Navier-Stokes, wave, and diffusion equations. They have the feature that the temporal evolution of the state at a certain point is determined only by the states at the point and the neighborhood. Parallel computing is effective for this type of calculation because each computer can calculate by exchanging only neighborhood information. In addition, the solutions of the above equations behave orderly on the macro scale. On the other hand, for the temporal evolution equations including nonlocal interactions, *e.g.*, the many body problem with long-range potential, temporal evolution of the state at a certain point requires global information. So, parallel computing is not good at this type of calculation.

In our framework, by designing the appropriate local interactions as a rule of decision making at nodes, we get the flow control mechanism to work effectively as an autonomous decentralized system. The performance of the whole network becomes the solution of a certain temporal evolution equation.

Our flow control [2, 3] is based on the diffusion-type equation and we expect the congestion in the network to be restored with time, like diffusion phenomena. Although the behavior of each node obeys a predefined rule and its decision is based only on local information, we can expect the performance of the whole network to exhibit an orderly property.

We show an example in a continuous approximation for simplicity. The packet flow $J(x,t)$ in our framework is written as

$$J(x,t) = \alpha\, r(x,t) - D_i \,\frac{\partial n(x,t)}{\partial x}, \qquad (1)$$

where $r(x,t)$ and $n(x,t)$ denote the drift component of the flow and the number of packets, at position x and time t, respectively, and α and D_i are constants. When each node handles the flow, the node requires only the information at x and its neighborhood. So, autonomous decentralized control applies effectively to this framework. The temporal evolution of the number of packets at x is written as

$$\frac{\partial n(x,t)}{\partial t} = -\alpha\,\frac{\partial r(x,t)}{\partial x} + D_i\,\frac{\partial^2 n(x,t)}{\partial x^2}. \qquad (2)$$

This is a diffusion-type equation and it will lead to the diffusion phenomena with respect to the number of packets.

5 Concluding Remarks

This article has shown the aims of our autonomous decentralized flow control from three different points of view. The diffusion-type flow control we proposed exhibits appropriate performance as shown in our previous studies. In addition, our current results show that shortening the control delay and applying the control to an asymmetric network are probably possible if we choose appropriate values of α and D_i. In future, we will investigate an appropriate way to determine the values of α and D_i.

References

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