Traffic Control Scheme under the Communication Delay of High-speed Networks

Kenji Horikawa **Masaki Aida**
NTT Multimedia Networks Laboratories
1-2356 Take Yokosuka-Shi
Kanagawa 238-03 Japan
{horikawa,aida}@nttmhs.tnl.ntt.co.jp

Toshiharu Sugawara
NTT Basic Research Laboratories
3-1 Wakamiya Morinosato Atsugi
Kanagawa 243-01 Japan
sugawara@ntt-20.core.ntt.co.jp

Abstract

In this paper, we discuss the concept of multiagent systems as applied to high-speed network traffic control. In the high-speed domain, the propagation delay in a network causes significant problems. One of them is that any centralized control is too late to maintain normal network operations, so distributed traffic control by autonomous agents is required. The basic idea of our traffic control for high-speed networks is a combination of distributed local control and centralized global control; that is, before the global control becomes effective, all network nodes try to maintain their operations in cooperation with other nodes. The significance of propagation delay in such networks requires that the communication delay is included in the model of the node agents. This paper proposes a multiagent traffic control and illustrates the experimental results. The results show that the control based on the multiagent system can improve the efficiency of network control.

Introduction

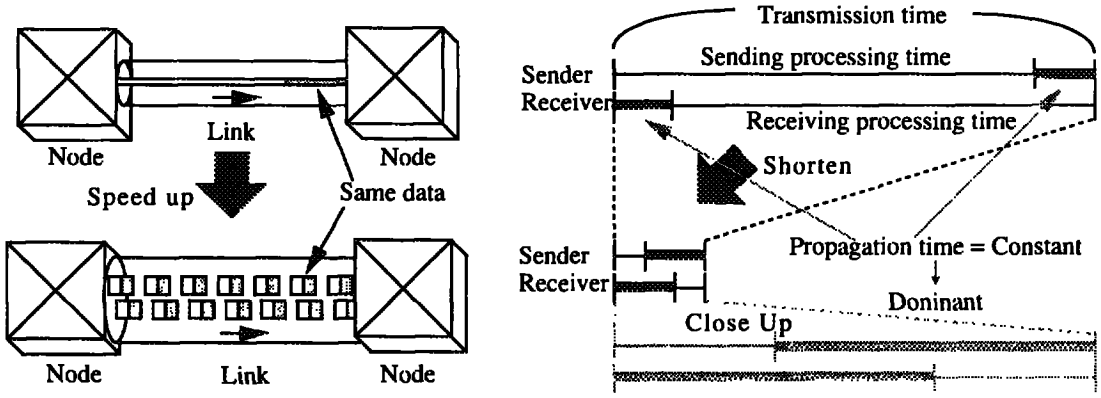
The focus of our work was the application of the concept of multiagent systems to high-speed network traffic control. A multiagent system is a collection of separated autonomous agents that achieve their common/individual goals with local decisions and with some interactions with the neighboring agents (Bond & Gasser 1988). Although research on systems of this type is required in real domains in accordance with the advance of computer and networking technologies, very little has focused on actual applications and/or situations. It is quite important to show or suggest in what application a multiagent system is useful, and how.

Network control of high-speed networks such as ATM (Asynchronous Transfer Mode) networks (CCITT 1992) is an important application of multiagent systems. Global control with complete information may be able to achieve more effective network operations. This control operation is, however, too late, because the centralized control system has to acquire global information, process it, and then determine what network control operations should be performed; these are costly tasks. In a high-speed network, propagation delays that need to collect global information and to affect distant agents become relatively long in comparison with processing time. As a result, the busy nodes may enter another state or may receive excessive data before the global control become effective. Network control based on a multiagent model is a possible solution for future high-speed telecommunication.

Our basic idea of applying a multiagent system to network control is a complemental combination of local network control with local interactions (multiagent network control) and global network control. The nodes that detect a network problem (such as congestion) try to maintain operation by multiagent network control until global control arrives. To achieve the proposed control, it must be shown that multiagent control is robust enough to wait for global control operations.

Although a number of local traffic controls for high-speed networks have been proposed (ATM Forum 1994b; 1994c; 1994d), our local control has two important features. First, each node (agent) takes into account the propagation delay (or distance between agents) and always acts in anticipation of the near-future situation, because all messages (requesting tasks or data values of other agents) are read by the receiving agents with some delay. Second, our control is cooperative. Other control methods are, in some sense, selfish because each node tries to maintain its individual operation according to local data only, based on the tacit assumption that if all nodes work efficiently the network also works efficiently. Thus we can say that this is a single agent model. However, in our control, a node decides its actions on the basis of data gathered from neighboring nodes as well as local data, so this control is based on a multiagent model. Our experimental results show that although a node may select on operation that uses up its local buffer (so the local situation may become worse) in the proposed control scheme, the operation of the network as a whole becomes more efficient.

An example network operation problem is illus-



(a) Many cells on a link

(b) Donination of propagation time

Figure 1: Effect of high-speed network

trated in the next section. Then a new multiagent model for network control is proposed for the control of high-speed networks. Some simulation results are also shown and analyzed. These results indicate that the proposed network control based on the multiagent model is more robust in network congestion than the conventional local traffic control and can prolong normal operation. This means that the proposed complemental network control can work in a high-speed network.

Problem

Our problem is the traffic congestion occurring in a high-speed network such as an ATM network. Recent progress in telecommunication technology, represented by ATM switching and optical fiber transmission, have made networks high-speed and broadband. As illustrated in Figure 1 (a), in communications within a low-speed network, or between close nodes, the first signal reaches the (link-by-link) next node, and the processing for receiving starts, before the transmission is completed. In a high-speed network, however, since the improvement in node performance only shortens the duration of the processes for sending and receiving, propagation delay becomes dominant in transmission time (Figure 1 (b)).

This situation suggests at least two problems (Pecelli & Kim 1995) for congestion control in high-speed networks. The first of these is when many ATM cells exist (Mitra 1990) on a link as a result of the processing time of the cells being much shorter than the propagation time between them. Suppose that two network nodes separated by 100 km are connected with 1-Gbps lines. When traffic congestion occurs in this network, up to 1500 ATM cells[1] may exist on the link, as shown in Figure 1 (a), because the propagation speed in optical fiber is approximately 70% of light speed. This means that, even if the upstream node immediately stops the flow of cells due to a signal from the downstream busy node, about 3000 cells will still arrive at the downstream node. Furthermore, these cells cannot be controlled, so they may cause loss of data, or system failure as a result of exceeding the processing performance of the nodes. Second, the internal state of a node changes very frequently, thus it is possible that the state will change while the notification of the condition and the control signal propagate down the link. This means that the remote control is not applicable in a critical situation. These two problems also show that the global control is too late for high-speed network operations, since the network center is usually located at a greater distance than the neighboring nodes. Before the global control arrives, the busy node may receive too many cells and/or may have another internal state. Thus, local control is required.

[1] In the ATM network, communication data is divided into datagrams called cells and is forwarded in the network. A cell has a fixed length, 53 bytes (payload is 48 bytes).

The Multiagent Model for Network Control

Multiagent Model with communication delay between agents

The discussion in the previous section also shows that the distance between agents or the propagation delay is an important factor for modeling the multiagent systems in a real domain such as traffic control of a high-speed network. The control delay is caused by not only the processing overhead in each agent (we use the word "agent" instead of "node" hereafter) but also by the distance between agents. Figure 2 shows the conceptual model of the multiagent system with communication delay between agents. In this model, an agent has (i) information for deciding its own actions ($I_1 \cdots I_l$), (ii) a set of internal states ($s_1, \cdots, s_m$), (iii) a current state (s_i), and (iv) a set of messages

$(m_1, \cdots, m_n)$. The information (i) for deciding actions consists of: local data that concern the local agent and are locally observed; non-local data that concern, and are observed by, other agents; and knowledge of the domain for problem solving. Additionally, the following two factors should be taken into account for the agent's actions:

(v) **The delay of communications between agent A and B, d_{AB}.** This value means that a message from an agent A at time t will arrive at agent B, at or after $t + d_{AB}$. (In general, d_{AB} does not have to equal to d_{BA}, but we can assume $d_{AB} = d_{BA}$ without loss of generality in the discussion below).

(vi) **The collection of the functions $\{f_k(d_{AB})\}$ describing the effects caused by the propagation delay.** For example, suppose two networked agents area at a distance of 100 km and are connected with a 1-Gbps line. If agent A sends a control signal to agent B, A will receive its effect after $2d_{AB}$

Network Agent Model

This section describes the network agent model for our application using the multiagent model from the previous section. The assumptions of this model (ATM Forum 1994c) are as follows (see Figure 3):

- Each agent can notify its upstream agents of the transmission rate r_{AB}. Each agent must send the data at a rate no higher than the transmission rate specified by its downstream agents.
- There is a propagation delay, expressed as d_{AB}, meaning the communication delay from agent A to agent B. We assume that the delays between agents are a priori given as constant values.
- Each agent has information for traffic control. Example values are shown in Table 1.

Table 1: Example information for traffic control

Dynamic information	Occupied buffer space
	Record of rate signals to the upstream agents
	Transmission rate specified by the downstream agents
Static information	Total buffer capacity
	Bandwidth (Link speed)
	Distances among agents

The internal state is also described by this information. For example, the congested state can be expressed as Occupied buffer space > 75% of Total buffer capacity.

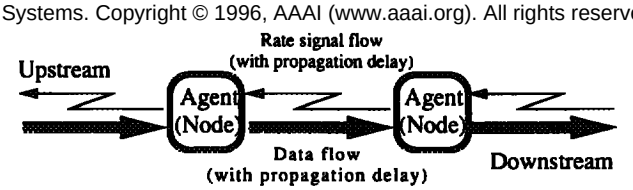


Figure 3: Flow control model

Network Control

This section proposes a new traffic control scheme for high-speed networks. The basic idea of the scheme is that an agent can specify the transmission rates of the upstream agents based on its local information (such as its current transmission rate and its remaining buffer capacity) and the predicted values (such as the remaining buffer capacity after the round trip time T, or RTT, which is $2d_{AB}$). The objective of the proposed control is that agents can control the network flow through interactions and thus achieve efficient network operations.

Each agents interacts with the neighboring agents via informing transmission rates to the upstream agents and transmitting user data to the downstream agents. The global goal of all agents is high throughput and low cell loss ratio condition of the network.

Calculation of the remaining buffer capacity

Due to the propagation delay caused by the physical distance, the transmission rate of which an agent notifies the upstream agents at time t becomes effective at time $t + T$. It takes the same time as RTT before the effect returns to the sending agent (i.e. the control begins to be effective). Therefore, the agent has to predict the remaining buffer capacity at $t+T$. This capacity is called the *remaining capacity* in this paper. The remaining capacities $X(t+T)$ and $Y(t+T)$ after time T are calculated by the following effect functions.

$$Y(t+T) = L - Q(t) - \int_0^T R(t-\tau)d\tau \quad (1)$$

$$X(t+T) = Y(t+T) + f(t)T \quad (2)$$

L	:	The total buffer capacity
$Q(t)$	:	The occupied buffer space at the time t
$R(t)$	:	The transmission rates of the upstream agents, specified by the node at time t
$f(t)$	:	The transmission rate to the downstream agents at time t

$Y(t+T)$ shows the worst case, that is, the lowest remaining capacity after T, assuming that the transmission rate downstream becomes minimum ($f(t) = 0$). $X(t+T)$ shows the lowest remaining capacity after T under the assumption that the rate specified by the downstream agent does not change.

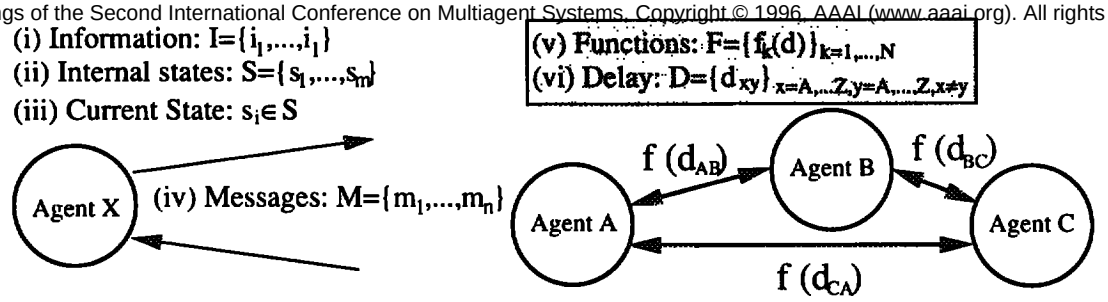


Figure 2: Multiagent model with communication delay between agents

Update rules of the transmission rates of upstream agents

Since the rate signal cannot always be sent within the minimum interval, we define the rate update interval W time, meaning that, in the normal case, the transmission rate is sent to, and updated in, the upstream agent at every W. When the transmission rate to the downstream agent is relatively low or the network is busy, however, the buffer may rapidly become occupied and then may overflow. To avoid this situation, the agent updates the transmission rate of the upstream agent without waiting for the rate update interval, when the following inequality holds:

$$Y(t+T) < 0 \tag{3}$$

The new transmission rate of the upstream agent $R(t)$ is given by this formula:

$$R(t) = f(t) + \frac{X(t+T)}{W} \tag{4}$$

In which we assume that the rate remains between the maximum and minimum values of the rate for the link. Each rate is adjusted to the maximum or minimum value respectively, if it exceeds.

The transmission rate $R(t)$ of the upstream agent is the sum of the rate in proportion to the remaining capacity after RTT and the transmission rate specified by the downstream agent. $X(t+T)$ is usually positive since there will be remaining capacity after RTT. However, it becomes negative if the estimated occupied buffer space exceeds the total buffer capacity. Thus, it is important, even in a busy situation, not only to lower but also to raise the upstream transmission rate according to the rate $f(t)$ specified by the downstream agent; the rate is controlled to make the occupied buffer space approach the total buffer capacity. Here, the transmission rate of the upstream agent is calculated to consume the remaining capacity within the rate update interval W. When the occupied buffer space is small, the operation to raise the rate ($R(t) = f(t) + \alpha$) is carried out, and, when the occupied buffer space is near the total buffer capacity, the operation for equalizing the transmission rates of the upstream and the downstream agents ($R(t) \approx f(t)$) is carried out. Moreover, when the occupied buffer space is expected to exceed the total buffer capacity, the operation to lower the transmission rate ($R(t) = f(t) - \alpha$) is carried out to try to recover from the congestion state. Note that, in general, an agent has a number of the upstream agents, thus the transmission rate $R(t)$ should be calculated for each of the upstream agents. In this simulation, however, we assume that cells to be forwarded to different agents appear with the equal probability, so the more occupied buffer of each node is used to calculate both of transmission rates for the upstream agents.

In addition, to handle traffic bursts, we use $L - M$, the total buffer capacity subtracted margin M, as the total buffer capacity L denoted above. This is because there are statistical swings in switching (deciding the destination of each cell) in the model described the next section.

Experimental Evaluation of the Proposed Traffic Control

Simulation model

In this experimental simulation, the network is a torus consisting of 20 × 20 agents (nodes) as shown in Figure 4 (a). Each agent can decide its own actions autonomously through interactions such as information exchanges and control operation requests.

Each agent has a structure as shown in Figure 4 (b) and operates as follows:

- The agent has two buffers corresponding to the output destinations.
- Incoming cells are stored in the buffer according to their destinations. In this simulation, those cell is to be forwarded to the right and those to be forwarded down appear at random but with the same probability.
- If the buffer for the destination has no space, the cell is discarded as a lost cell.
- Cells in the buffer are sent out at the transmission rate specified by the downstream agent.
- The agent can notify the upstream agents of the allowed transmission rates based on the traffic conditions (this is defined in Section 4.2).

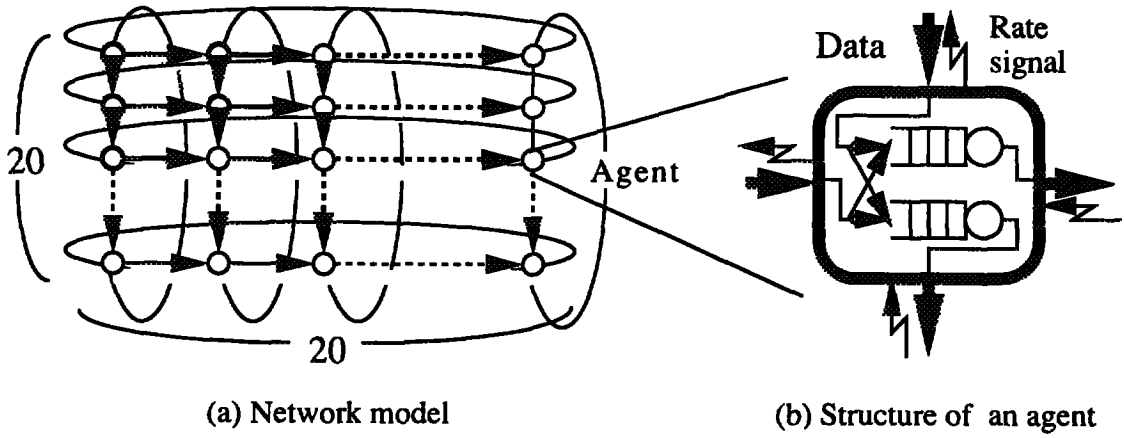


Figure 4: Network model

This network model models the area that is not affected by the edges of network near end nodes. As we consider notifying traffic sources of network congestion directly is too late for network control, we do not assume any particular behaviors of end nodes in multiagent type network control. Traffic source control will be done in global network controls as combination with that control.

The proposed control is compared with the following typical traffic control. This traffic control sets the transmission rate of the upstream agent in proportion to its remaining capacity (this control is called PRC control in this paper). The transmission rate of the upstream agent is calculated as follows:

$$\text{Rate:}R(t) = \text{maximum rate of the link} \times \frac{\text{present remaining capacity}}{\text{total buffer capacity}} \quad (5)$$

Note that, since ATM technology is now in progress, a number of traffic controls are proposed (ATM Forum 1994a; 1994b; 1994c; 1994d) but there has been no standard one yet. Their principles are notifying traffic source of network congestion or transmission rate information. In point of traffic control based on agents' internal condition, the control given by the above formula is fairly typical of proposed ATM traffic controls.

There are two main differences in our traffic control and PRC. First, PRC decides the transmission rate of the upstream agent according to the very limited local data: remaining capacity, total buffer capacity (static), and maximum rate of the link (static). However, in our methods, the agent tries to keep $f(t)$ and $R(t)$ equal, thus the rate specifications from the downstream agents affect the rate of the upstream agent. Of course, the actual transmission rate of the upstream agent[2] affects the downstream agents in turn by sending cells. Therefore, we can say that agents affect each other. Second, in our control, the agent expects the remaining capacity after time T, which is $2d_{AB}$. So we can say that the agent takes in to account the propagation delays (distances between agents).

Simulation Environment

Link Bandwidth and length: A horizontal link in Figure 4 is 300 Mbps and 20 km in length, and a vertical link is 600 Mbps and 2 km in length. They are assumed to be WANs and LANs respectively. Note that the horizontal links are the bottle necks of the traffic flow.

Cells in the network: The number of cells in the network is zero in the initial state. Then, five cells are added to agents chosen at random every one cell time[3].

Buffer capacity: All agents have the same buffer capacity (size is 300 cells). In the proposed traffic control, the margin M is assumed to be half of the buffer capacity.

Overflow: Although the cells are discarded when no space is left, the discarded cells are again added into the network to maintain the network load.

To evaluate traffic controls, we use a measure called *throughput of the network* that is given by the following definition (Mitra 1990):

$$\begin{aligned} &\text{Throughput of the network} \\ \stackrel{\text{def}}{=}\ &\text{Usage rate of all links in the network} \\ =\ &\frac{\text{Total number of cells on all links}}{\text{Maximum number of cells on all links}} \quad (6) \end{aligned}$$

[2]The actual transmission rate of the upstream agent is decided autonomously. Only the allowed maximum values are specified by the downstream agent.

[3]Cell time is a kind of unit and defined as the time to send out one ATM cell

The throughput of the network is the extension of the conventional throughput to evaluate the whole network activity from the macro viewpoint.

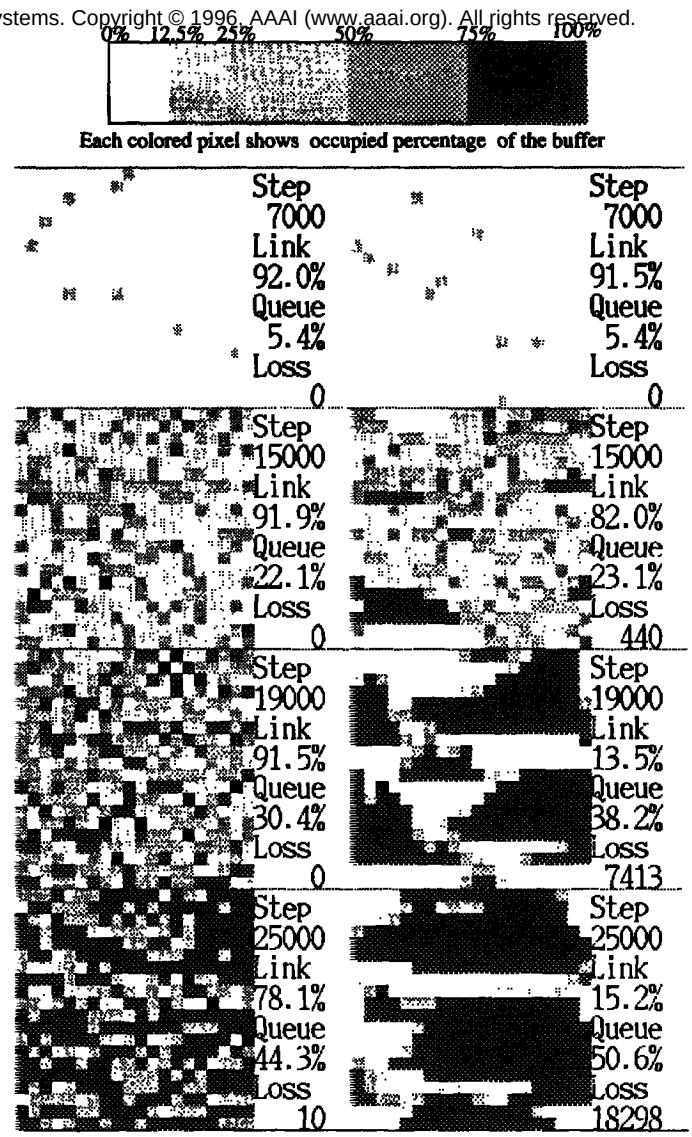
Experimental Result

Robustness of global performance The results obtained in the simulation are shown in Figure 5. Note that the number of cells increases as time progresses. As shown in Figure 5 (a), most of cells remain on the link between 0 and 4,000 cell times because the network is not busy, and incoming cells are immediately sent out. After 5,000 cell times, the throughput becomes constant at about 92%. This means that cells begin to be stored in buffers.

After 15,000 cell times (after the number of cells in the network exceeds 750,000), the throughput of the network controlled by the PRC begins to drop. Finally, its throughput is lowered to nearly 0 and the control fails. On the other hand, even at 25,000 cell times (number of cells is 125,000), the proposed traffic control maintains high throughput without failure. In addition, the proposed control causes hardly any cell loss, as shown in Figure 5 (b). The throughput of the proposed control begins to drop and the control is fails at 30,000 (150,000 cells). Since the total capacity of the buffer for the bottle neck links is 120,000 cells, however, it is safe to say that the proposed control can endure in higher load conditions and can maintain normal network operation.

Behavior of congested agents Figure 6 shows the behaviors of busy agents in the simulation. A pixel corresponds to one agent and the internal state is expressed by the color density.

Since the number of cells in the network increases as the simulation advances, it becomes blackish overall. It is possible to see that the areas of congested agents spread in the PRC method. On the other hand, in the proposed method it can be understood that there are some congested agents but they are not concentrated, and the expansion of congestion is minimized to prolong control without cell loss. Like the PRC method, where the transmission rate of the upstream agent is calculated based only on the remaining capacity, the congestion spreads toward the upstream agents, because the agent in question tries to improve its situation by lowering the transmission rate. If the congestion propagates upstream faster than the recovery of the downstream agents, congestion will spread out. In the proposed method, the transmission rate of the upstream agent is not only lowered but also raised according to the transmission rate specified by the downstream agent, the remaining buffer capacity, and the congestion state. Although an agent may select an action that and consumes more of its local buffer, such an action can avoid the spread of congestion and thus is coherent from the global view point.



Proposed scheme (left) and PRC scheme (right)

Step: Simulation time
Link: Link usage of the whole network
Queue: Average usage of all buffers in the network
Loss: Number of lost cells (running total)

Figure 6: Spread of congestion

Discussion

In the simulation, if agents do not take into account T (i.e. communication delay), the number of lost cells increases. Another interesting observation is that, if the speed and the distance of the horizontal and vertical links are identical, no great differences between the multiagent control and PRC are observed. This shows that, like real networks, various types of network speed and distance make the network behavior more complicated. We expect that the multiagent type of network control is more important in controlling such a network.

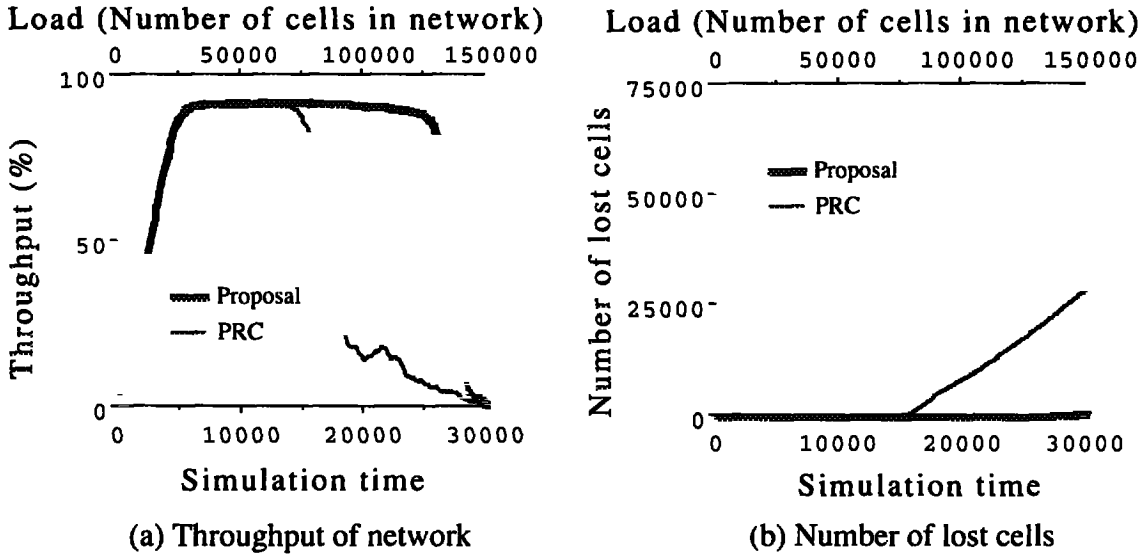


Figure 5: Simulation result

We can consider another extension of the proposed traffic control method. For example, in a more critical situation, agents can take more coordinated actions if they can negotiate with each other, such as requesting the *downstream agents* to raise/lower their transmission rates. In this case, some type of negotiation may be required (Conry & Lesser 1988; Klein 1991), but there are tradeoff between quality control and efficiency. This is a topic for further research topic.

Conclusion

To use high-speed networks efficiently it is necessary to develop fast and efficient traffic and congestion control schemes. Although traditional schemes adopt the notification principle to cope with congestion, it is less effective in high-speed networks.

This paper describes our attempt to cope with the complexity of congestion controls in high-speed networks such as ATM networks, by applying the concept of a multiagent system. We introduced the concept of the communication delay between agents into a multiagent model, because the propagation delay is significant in this domain. In our proposed traffic control scheme, traffic control works on the basis of the outgoing transmission rate, specified by the neighboring downstream agents. It also anticipates the near-future situation by taking into account communication delays (distance between agents). Agents try to improve not the local performance but the global one. This point is quite different from the conventional scheme where it is assumed (not clearly but tacitly) that the efficient local individual operations lead to efficient global operation. Our experimental result show that this assumption is not always correct, especially in high-speed networks.

Simulation results indicate that our multiagent approach can deal with the complexity of a congestion control mechanism and that it is a promising method of network control in high-speed networks.

References

The ATM Forum, "A Generic Traffic Control Specification at the UNI," ATM Forum/94-0663, July, 1994.

The ATM Forum, "Enhanced Credit-based Congestion Notification (ECCN) Flow Control for ATM Networks," ATM Forum/94-0450, May, 1994.

The ATM Forum, "Closed-Loop Rate-based Traffic Management," ATM Forum/94-0438, July, 1994.

The ATM Forum, "Congestion Control With Explicit Rate Indication," ATM Forum/94-0692, July, 1994.

A. Bond and L. Gasser (eds.), *Readings in Distributed Artificial Intelligence*, Morgan Kaufmann Publishers, California, 1988.

CCITT SG XVIII, Recommendation I.150.

S. Conry, R. Mayer, and V. Lesser, "Multistage Negotiation in Distributed Planning," in *Readings in Distributed Artificial Intelligence*, Morgan Kaufmann Publishers, California, 1988, pp. 367-383.

M. Klein, "Supporting conflict resolution in cooperative design systems," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 21, No. 6, pp. 1379-1389, 1991.

G. Pecelli and B. G. Kim, "Dynamic Behavior of Feedback Congestion Control Schemes," *Proc. of IEEE INFOCOM'95*, pp. 253-260, 1995.

D. Mitra, "Optimal Design of Windows for High Speed Data Networks," *Proc. of IEEE INFOCOM'90*, pp. 1156-1163, 1990.