Synchronous Time Division Internet
for Time-Critical Communication Services

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Abstract

This article proposes a new framework of the Internet implementation for the purpose to be able to minimize the transmission delay time of time-critical packets. The framework consists of new routers which make possible to work both of two modes (shared mode and exclusive mode) on a same network media, and a protocol to synchronize the timing to change the active mode of routers. Usually, the router acts as a conventional router of the Internet in the shared mode. On the other hand, in the exclusive mode, the router acts as a repeater and transfers packets without any rewriting of packet headers. By changing appropriate routers to the exclusive mode, a certain source and destination pair in the network can be connected as if they are connected directly with an isolated LAN. The timing of the mode changing is managed by a QoS (Quality of Service) management protocol so as to change all of the appropriate routers to the exclusive mode synchronously. As the results, the Internet can provide reserved time-critical communication services by providing synchronous time-division slots of exclusive mode to the connection.

1. Introduction

Recently, fine-grain distributed control has become possible to realize. For example, the author showed a bilateral control system which two homogeneous robots move synchronously with communicating each other in every $1ms$ control loop[1]. The system used an isolated Ethernet LAN because multi-hop network can not ensure the reachability of packets in a certain transmission delay time.

To resolve this restriction and to realize geographically distributed control systems, this article proposes a new framework of the Internet called *synchronous time division Internet (STDI)*. STDI is based on *pros* and *cons* of conventional network hardware categorized as follows:

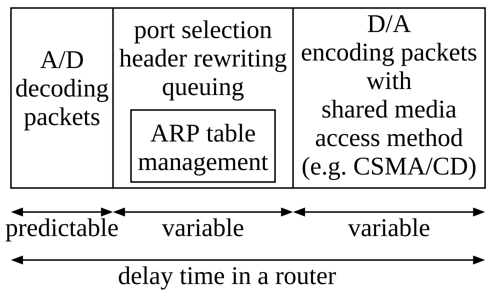
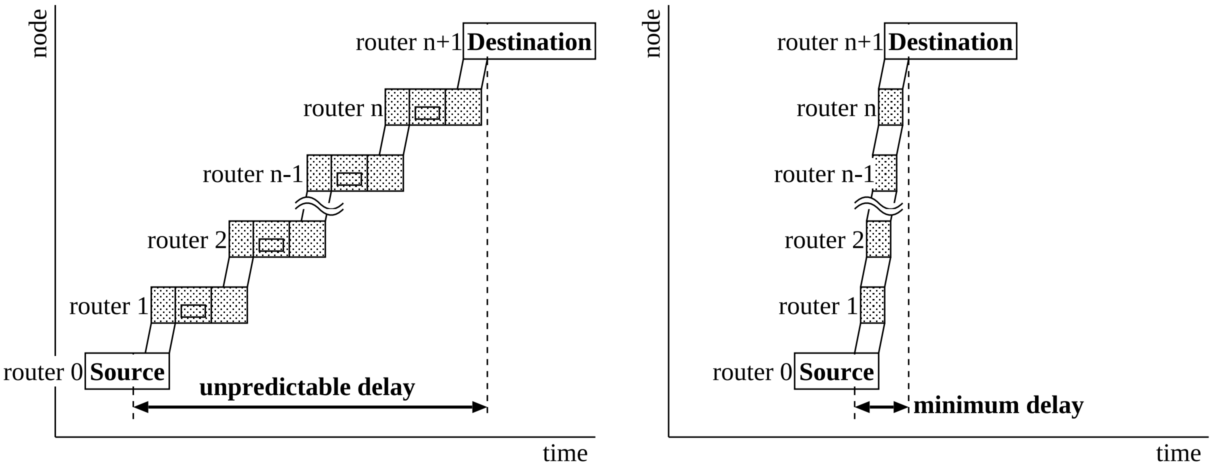


Figure 1. Processing Time in a Conventional Router

router, bridge They can forward packets for infinite hops. But they spend unpredictable long delay time (Fig.1). Store-and-forward type switch is included in this category.

dumb hub, repeater They spend only static short delay time. But they can forward packets only for a few hops because of the distortion and the attenuation of signals. Cut-through type switch is included in this category.

To make the best use of the advantages of both categories, a new packet forwarding hardware, called *synchronous hybrid router (SHR)*, is introduced. Also, to minimize the transmission delay time for time-critical packets, appropriate SHRs *are changed synchronously* to act as repeaters when time-critical packets are transmitted (exclusive mode), and to act as conventional routers in other term (shared mode). The effect of the proposed two technologies is expected as Fig.2. In shared mode, all of the routers cause unpredictable transmission delay (in Fig.2(a)). Many of conventional Internet applications, including TCP/IP flow control algorithms and streaming technologies, are designed as to adapt for the unpredictability. On the contrary,



(a) in Shared Mode (b) in Exclusive Mode

Figure 2. Transmission Delay in Multi-hop Network

in exclusive mode, since all of routers and network media are reserved for a source node to send time-critical packets, any media access methods are not required at all. So the packets sent from a source node can reach to a destination node exactly after the minimum delay (in Fig.2(b)).

2. Synchronous Hybrid Router

A SHR is a packet router to be designed as to achieve the minimum delay from the source node to the destination node of time-critical communications. At the same time, the SHR have to be designed to have an interoperability with conventional IP routers. To meet both of these requirements, it is designed as a combination of three parts: a router, a repeater and a synchronous changer. The router part works as a conventional router. It is unavoidable that the delay of a packet forwarding is unpredictable and variable in case of using this part. On the other hand, the delay in case of using the repeater part, described below, can be fixed or predictable. The synchronous changer part selects one of above two parts to work, i.e., the router part is activated in shared mode and the repeater part is activate in exclusive mode. The timing of the changing is synchronized with all of SHRs by a network resource management system likes RSVP[2].

2.1. Fundamental Design of Repeater Part

If all of network resources are reserved at the time slice (described in 3), the media access method such as CSMA/CD is unnecessary in repeater part. So it is possible for SHR to forward a packet from the input port to the output port in the minimal delay time by just repeating input signal to output ports like a conventional repeater. In this case, the delay time ${}^{rep}D_i$ at a router i in repeating a S bytes of packet is fixed although the signal can be repeated only if the bit rate of input port R^{in} is same as that of output port R^{out}.

$$ {}^{rep}D_i = D_i^{decode} + D_i^{rep} + D_i^{encode} = D_i^{rep} + 2\frac{S}{R^{out}} \quad (1) $$

Where D_r^{rep} is repeating overhead and can easily be designed as a constant (see Fig.1). So the total transmission delay D^{total} is given as a predictable value from the size of a packet.

$$ {}^{rep}D^{total} = \sum_{i=0}^{n} {}^{rep}D_i = \sum_{i=0}^{n} D_i^{rep} + \sum_{i=0}^{n} M_i + \frac{S}{R^{out}} \quad (2) $$

$$ = {}^{rep}AS + {}^{rep}B \quad (3) $$

Here D_i^{encode} and D_{i+1}^{decode} are overlap with shift M_i which is a transmission delay in network media between router i and $i+1$. So the total delay can be calculated easily from the first order function of the packet size. The second and the third terms in Eqn.(2) are exist even in the delay with a fiber cable. So only $\sum D_i^{rep}$ (typically several ns) is the overhead of exclusive mode of STDI.

Please note that the SHR have to be equipped for a signal shaper to compensate the distortion and the attenuation of the input signal so as to make packets to hop many SHRs. Even so, the repeater part can be design as to make D_i^{rep} constant. Also note that there is a precondition that the bit rates of all network media are the same.

2.2. Extended Design of Repeater Part

To resolve the precondition, the repeater part should be extended. If R^{in} is differ from R^{out} then a store-and-forward type packet forwarding have to be used. Usually the delay time in store-and-forward type switch ${}^{saf}D_i$ is not predictable because of queue processing and media access processing.

$$ {}^{saf}D_i = D_i^{decode} + D_i^{queue} + D_i^{encode} + D_i^{ma} \quad (4) $$

Where D_i^{ma} is the media access processing time (see Fig.1). D_i^{queue} depends on the load of the router i and D_i^{ma} depends on the condition of the network media between router i and $i + 1$. But since the network resources are reserved to use and d the router process only the time-critical packet with a SHR, D_i^{ma} can be zero and D_i^{queue} can be fixed. So the delay time can be predictable with the following first order equation.

$$ {}^{saf}D_i = \frac{S}{R^{in}} + D_i^{queue} + \frac{S}{R^{out}} \quad (5) $$

$$ {}^{saf}D^{total} = \sum_{i=0}^{n} {}^{saf}D_i \quad (6) $$

$$ = \sum_{i=0}^{n} \left(D_i^{queue} + \frac{S}{R_i^{out}} + M_i \right) \quad (7) $$

$$ = {}^{saf}AS + {}^{saf}B \quad (8) $$

As the results, there are two ways to implement a repeater part, i.e., the fundamental repeater type and store-and-forward type without media access method. Both of them can work as a SHR because the delay time of the repeater part is successfully bounded as Eqn.(3) and (8). So the total delay time from the source to the destination can also be bounded as the first order function of the packet size.

Obviously ${}^{saf}A \gg {}^{rep}A$ and ${}^{saf}B \gg {}^{rep}B$, so the fundamental repeater type behavior is much better than the store-and-forward type one. SHR i should be designed to support both of repeater types and to use fundamental repeater type if R_i^{in} and R_i^{out} is the same.

2.3. MAC Address Aliasing and Port Selection

In general, a router have to select the output port and rewrite the source and destination MAC addresses of a forwarding packet along with an ARP table in the router because physical layer of network refer MAC addresses to receive or forward a packet. Fig.3 shows the overview of MAC address rewriting where MAC_i^{in} and MAC_i^{out} are MAC addresses of input port and output port on router i. SHRs in shared mode also have to select the output port and rewrite MAC addresses as same as the conventional routers.

On the other hand, SHRs in exclusive mode should not refer its ARP table because referencing the table may cause unpredictable delay. Furthermore, it is better to omit packet rewriting to shorten D^{rep} or D^{queue} and to simplify its implementation (Fig.4). To omit packet rewriting, the following two questions arise.

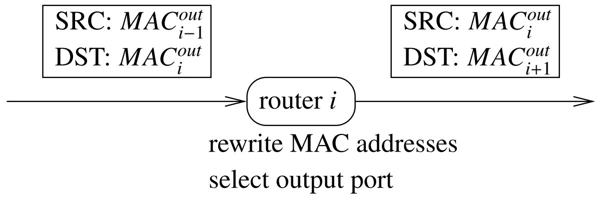


Figure 3. MAC Address Rewriting in router i

- How to receive packets destinate to another MAC address
- How to select the output port

To answer these questions, all of SHRs have to know the MAC addresses of the source and destination nodes and the route of the time-critical communication in advance. So it is necessary that these information is included into the resource management protocol.

Furthermore, if an intelligent switch exists between two SHRs, the switch have to learn the MAC addresses of the source and the destination of time-critical communications even though these nodes do not connected to the switch directly. So explicit or implicit teaching is required for all of these switches.

3. Synchronous Time Slot Reservation Method

To ensure certain QoS between the source node and the destination node of a time-critical communication, a resource reservation system is necessary. In STDI, all of routers and network media, which consists a route from the source to the destination of a time-critical communication, have to be reserved only when the time-critical packets are sent (the minimum delay term in Fig.2(b)). In other words, time slice of network route is defined as a resource in STDI, although bandwidth, measured in relative long period, is defined as a resource.

The most typical applications which require a time-critical communication are closed loop control systems. For example, bilateral robot system[1] is consists of two nodes which communicate with each other every 1ms period. Each packet size is relative small (less than 100byte) so one reservation term is short (less than 1μs). In general, communicating control systems require a short communication periodically.

So SHR is designed to support time slot reservation for all network lines and nodes. For the above example, time slot of 1μs per 1ms should be reserved to support the application. During the reserved term, all of SHRs are changed to an exclusive mode. On the contrary, they are changed to the shared mode during the rest term (i.e. 999μs per 1ms). Fig.5 show the typical example of mode transition cycle

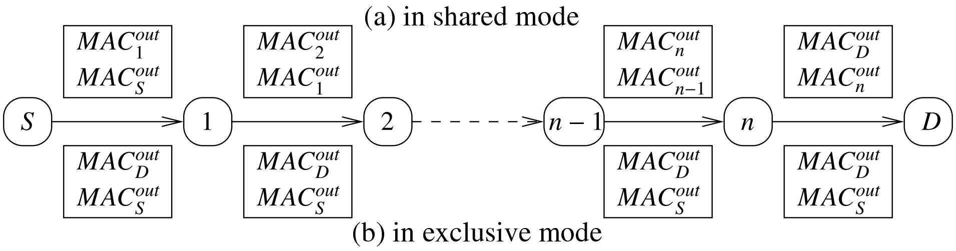


Figure 4. MAC addresses in each packet

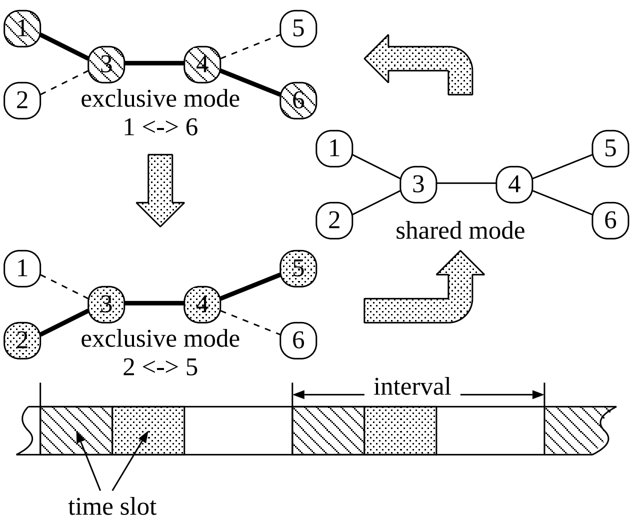


Figure 5. An Example of Mode Transition Cycle

when two time-critical communication exist in a network.

3.1. Synchronization of clocks

To achieve the time slot reservation as described above, precise adjustment of clocks in every SHRs is indispensable. NTP[3] provides adjustment method of computers, but 5*ms* of offset is a limit of NTP in normal usage. Horauer and Höller achieved the accuracy of synchronization in the range below $100\mu s$ with some hardware support [4]. NTP over synchronous time slot of STDI is expected to achieve high accuracy of synchronization.

4 Applications

Although STDI is designed for the purpose to realize time-critical communications through the Internet infrastructure, it is possible to apply STDI to various applications. The followings are

IP Telephony Voice over the Internet is one of the new application of the Internet. In general speaking, it is in the relation of the trade-off with the delay and the stability. STDI can provide both of short delay and high stability.

Multiplexing Virtual Private Networks When the exclusive mode is assigned to the arbitrary number of nodes and MAC address aliasing turns off, these node can be connected as if there is a private network.

5. Conclusion and Future Works

This article proposed STDI, a new framework of the Internet, to minimize the transmission delay time for time-critical packets. SHR, a multi-functional IP router, was designed to realize STDI. This article showed the transmission delay between distanced two nodes can be successfully bounded with STDI and SHR. Especially when all of network media has the same bit rate, the delay is near to that of a lease line.

References

[1] T. Yakoh, H. Sato and T. Aoyama, *Fine Real-Time Processing in Distributed Systems*, WFCS, 2000.

[2] R. Braden Ed., *Resource ReSerVation Protocol (RSVP) - Version 1 Functional Specification*, RFC-2205, IETF, 1997.

[3] D. L. Mills, *Network Time Protocol Specification*, RFC-1305, IETF, 1992.

[4] M. Horauer and R. Höller, *Integration of high accurate Clock Synchronization into Ethernet-based Distributed Systems*, International Conference on Advances in Infrastructure for e-Businnes, e-Eudcation, e-Science and e-Mediscine on the Internet, 2002.