TCP/IP PROTOCOL OVER IEEE-1394 NETWORK FOR REAL-TIME CONTROL APPLICATIONS

Bok-Jin Youm * **Jaehyun Park** **

* *Hyundai Heavy Industry, South Korea*
** *School of Information and Communication Engr., Inha Univ., South Korea*

Abstract: A computer network between the control devices plays an important role to provide the real-time operation in distributed computer control systems. Compare to the field-buses used in past, TCP/IP protocol, widely used in IT(Information Technology) area, provides an economical approach to implement a real-time control network. This paper proposes a modified TCP/IP protocol for IEEE-1394 network that supports asynchronous as well as isochronous data transmission. The experiment results show that real-time data could meet their deadlines even normal non-real-time data are mixed with them. The proposed TCP/IP over IEEE-1394 bus can be adopted for the real-time control applications including the home networking, intelligent robot, and general distributed control systems.

Keywords: Real-time communication, Computer communication networks, TCP/IP, IEEE 1394.

1. INTRODUCTION

A computer network between the control devices plays an important role to provide the real-time operation in distributed computer control systems. In past, expensive field-buses were usually used as the communication network between the controllers and sensors. Although these field-buses guarantees the real-time data transmission, they have many shortcomings: (1) expensive to implement, (2) hard to code applications, and (3) there is no world wide standard even there are many application specific standards. However, as the Internet technology progresses, the network protocols for Internet, TCP/IP and Ethernet pair, are likely to be used for the control systems too(Park and Yoon, 1998). Compare to the existing field-buses, TCP/IP and Ethernet pair have many strong points for the control applications; inexpensive to implement, vendor neutral worldwide standards, and compatible with large selection of off-the-shelf applications. Even though TCP/IP and Ethernet protocols are attractive to the control system designers, they are not yet easily used for the real-time control systems directly because the real-time communication between the control nodes is not guaranteed. This non-real-time characteristics is mainly caused by packet collision on the Ethernet bus and inefficient flow control in TCP/IP protocol layer. To overcome this non-real-time characteristics, several improvements are proposed such as RTP(Realtime Protocol)(Schulzrinne *et*

[1] Email to the corresponding author is *jhyun@inha.ac.kr*.
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al., 1996) and RSVP(Resource Reservation Protocol) (Braden *et al.*, 1997; Jacobson, 1988). Even these protocols improve the real-time performance of the TCP/IP on the top of Ethernet, due to the inherent non-realtime characteristics of Ethernet and TCP/IP, reliable real-time performance is hardly achieved.

Meanwhile, IEEE-1394 bus is a high speed serial bus whose speed is up to 400 MBits/sec (IEEE, 1995; IEEE, 2000). Even it is originally developed for the multi-media applications, its peer-to-peer network topology is suitable as a the real-time control network as well. Furthermore the isochronous transmission feature that mainly focuses on the multi-media data transmission like audio and video stream is also able to be used for the real-time control communication because many controllers and sensors exchange their control and monitoring data periodically. This means IEEE-1394 bus can be an alternative solution instead of the expensive field-buses as well as non-real-time TCP/IP over Ethernet if TCP/IP protocol supports IEEE-1394 bus well.

To use TCP/IP on the top of IEEE-1394 protocol, a couple of encapsulation methods of TCP/IP protocol are proposed(Johansson, 1999; Fujisawa and Onoe, 2001). Although these TCP/IP protocols work pretty well for the ordinary applications, they don't make the best use of the real-time characteristic of IEEE-1394 bus. For the real-time control purpose, three kinds of data, real-time with deadline, real-time data with fixed period, and non-real-time data, should be transmitted altogether with keeping real-time data meet their deadline and fixed period. Hence, to utilize the real-time feature of IEEE-1394 bus with TCP/IP, TCP and IP layer should provide a kind of real-time feature.

This paper proposes a modified TCP/IP protocol stacks specially designed for IEEE-1394 bus to support the real-time transmission in TCP/IP level. In spite of this modification, to maintain the compatibility with normal TCP/IP packets, it is limited to the unused field in TCP/IP headers. Section 2 introduces the protocol stack of IEEE-1394 bus. The internal structure and operation of the proposed IP and TCP are described in Section 3 and 4 respectively. The performance of the proposed protocol is evaluated by experiments in Section 5.

2. PROTOCOL STACK OF IEEE-1394

IEEE-1394 bus aims high-speed but low cost serial bus. It supports hot plug-and-plug as well as peer-peer communication without a central controller. For the data transmission, it provides two basic modes:

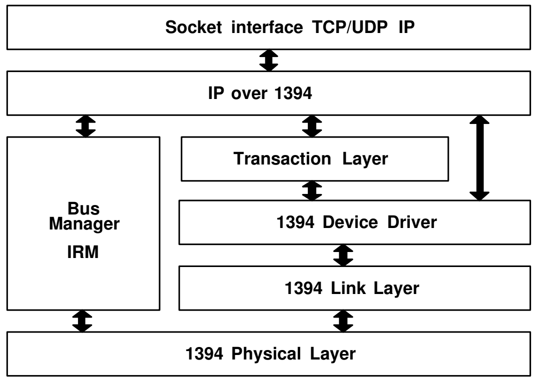


Fig. 1. IEEE 1394 protocol stack

Asynchronous transfer mode is used for transmitting the supervisory messages for the control and setup purpose. At least 20% of the total bandwidth can be used for this asynchronous transfer mode. Data exchange is a symmetric structure by Request and Response messages. Since this mode follows symmetric structure, it is able to provide a reliable communication.

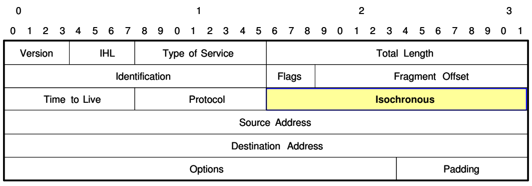
Isochronous transfer mode is used for the large amount of periodic data using the fixed or pre-allocated network bandwidth. Data transmission is synchronized with the Cycle Start Packet(CSP) that is initiated by Cycle Master(CM) at every 125 $\mu Sec.$ This isochronous transfer mode can use upto 80% of the total bandwidth.

The network protocol layer of IEEE-1394 bus consists of three layers; physical layer, link layer, and transaction layer as shown in Fig. 1. Link layer provides isochronous service as well as unidirectional data transfer service, that includes addressing, data check, and packetization. Transaction layer provides READ, WRITE, and LOCK transaction for asynchronous transfer mode.

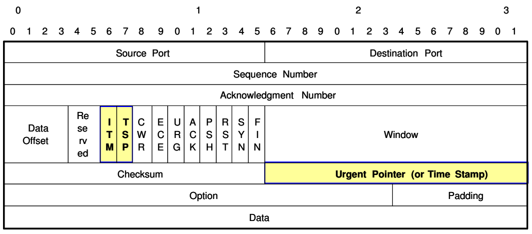
Besides these three layers, to manage bandwidth of network and support bus control functions, Bus Manager(BM) and Isochronous Resource Manager(IRM) are provided. BM's function includes the bus power and topology management. IRM takes care of bandwidth used for isochronous data transmission. The actual bandwidth is managed by Local Bandwidth Manager (LBM) with supporting of the IRM (isochronous resource manger) that can manage up to 64 independent isochronous communication channels.

3. MODIFIED IP FOR IEEE-1394 BUS

IP layer is a standard network layer of TCP/IP protocol that supports connectionless data service (Stevens, 1994). To support the real-time communication of IEEE-1394, IP packet has to convey real-time information to the link layer. However,



(a) IP-1394 header



(b) TCP-1394 header

Fig. 2. Structure of TCP/IP-1394 header

normal IP packet does not have any kind of information fields regarding real-time communication, with which it is impossible to identify real-time data from normal non-real-time data.

The IP packet of current version(IPv4) contains 20 bytes of header that is divided into several information fields; IP version, type of service (TOS), packet number, flags, offset, time to live (TTL), protocol, checksum, and addresses(Postel, 1981*a*). Among these fields, the header checksum field is not crucial if it is used in stable local area networks like Ethernet and IEEE-1394 bus because link layer guarantees reliable data transmission by its own error checking mechanism. This field is also obsoleted in IPv6, the next generation of IP, for header simplification purpose(Deering and Hinden, 1995). Instead of using header checksum field, these 16 bits are assigned as the Transmission Mode Field(TMF) in the proposed IP header, called IP-1394, as shown in Fig. 2(a). In spite of this modification, to maintain the backward compatibility with the ordinary IP packets, unused two bits in TOS are used to identify whether each packet is normal IP packet or IP-1394 packet. The structure of TMF(16 bits) are described below:

ISO(1 bit): The MSB indicates isochronous data packet. To transfer isochronous data packet, the isochronous channel and the enough bandwidth should be allocated prior to transmit the actual data packet. To guarantee the real-time transmission, IP-1394 layer would request link layer to allocate enough bandwidth of IEEE-1394 bus as much as indicated in the bandwidth field(lower 14 bits). The actual bandwidth allocation is arranged by IRM and LBM.

ASP(1 bit): ASP bit indicates that this packet is asynchronous packet. Asynchronous packet is stored in the queue and handled as a normal datagram packet.

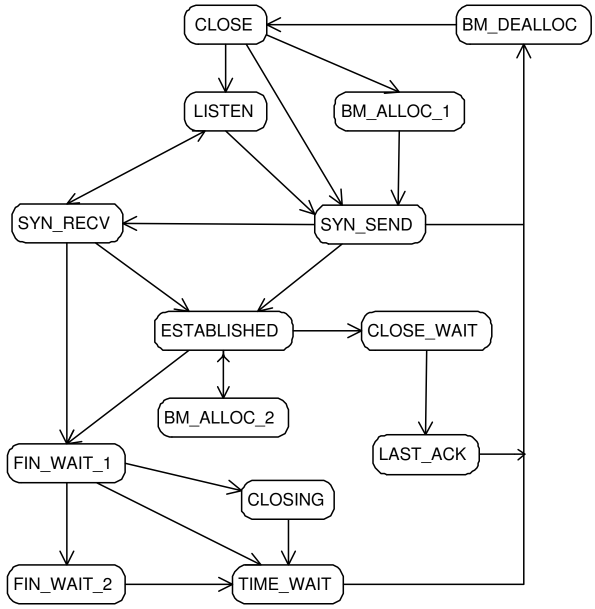


Fig. 3. State transition diagram of TCP-1394

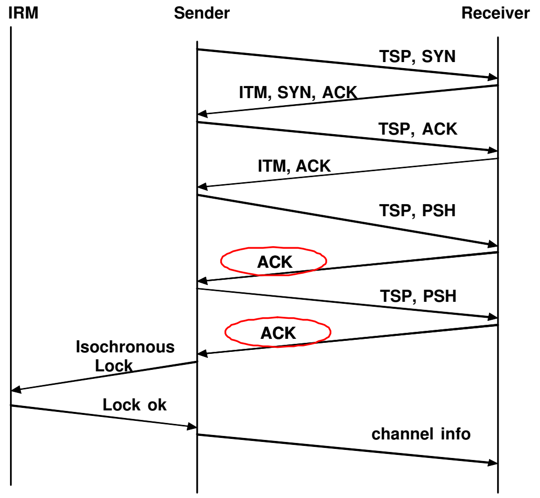
Bandwidth(14 bits): The remaining 14 bits are used to represent the bandwidth to be allocated for transmitting the isochronous packet. Since the basic isochronous cycle takes 125μsec and upto 80% of total bandwidth can be used for the isochronous transmission that equals 4915 cycles, 14 bits are enough to represent the bandwidth value(IEEE, 2001).

4. MODIFIED TCP FOR REAL-TIME DATA

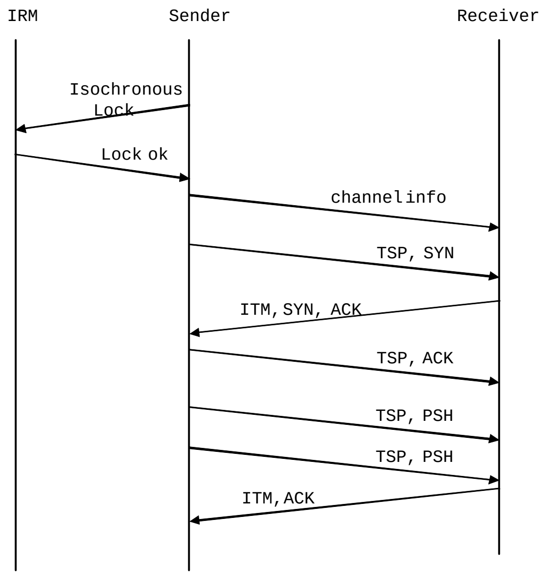
TCP protocol is a reliable connection-oriented protocol that transfers data in byte-oriented stream manner. To minimize the communication latency, it uses sliding window mechanism as a flow control. The standard TCP protocol and congestion control protocol are best-effort protocols that consume almost all of the available network bandwidth. This best-effort protocol may cause an unpredictable and unacceptable long latency when large data is transmitted.

To support real-time data in TCP level in spite of the inherit best-effort characteristics, standard TCP header is modified as shown in Fig. 2(b). Standard TCP header contains a field called "urgent pointer" that is used with URG flag to indicate urgent data(Postel, 1981*b*). If a URG flag is not set, however, these 16 bits of urgent pointer are not used. In the modified TCP header proposed in this paper, called TCP-1394, these unused 16 bits are used as *Time_Stamp(TS)* to indicate deadline of the packet. In addition to TS, there are two more flag bits; TSP(Time-Stamp) and ITM(In-Time).

TSP : TSP flag means TCP packet contains a time critical data that has a deadline. The actual deadline is stored in TS field.



(a) Realtime Data



(b) Periodic Data

Fig. 4. Timing Sequence

ITM : ITM is used by the response packet to indicate whether the received real-time packet meets its deadline or not.

Time Stamp : Time-stamp value is 16 bits-long and used for representing isochronous cycle time of IEEE-1394 bus. Since only upper 16 bits are used, the resolution of deadline is 2 *msec* and maximum value of is 127 *second*.

Fig. 3 shows the state diagram of TCP-1394. Three states, BM_ALLOC_1, BM_ALLOC_2, and BM_DEALLOC, are added to the standard TCP states to handle the isochronous transmission of real-time data. BM_ALLOC_1 state is added in order that the sufficient bandwidth should be allocated in advance. In the passive TCP mode, the network bandwidth enough to receive real-time data is allocated in BM_ALLOC_2 state. After finishing real-time data transmission, the bandwidth allocated should be returned in BM_DEALLOC state.

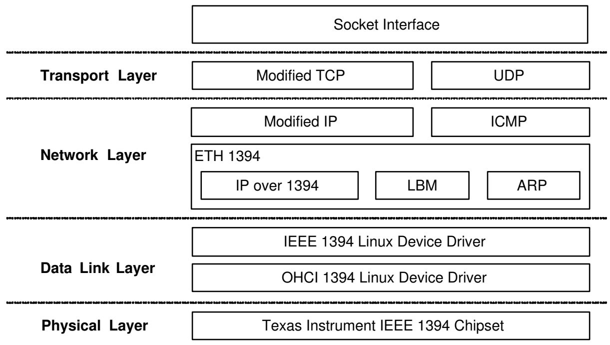


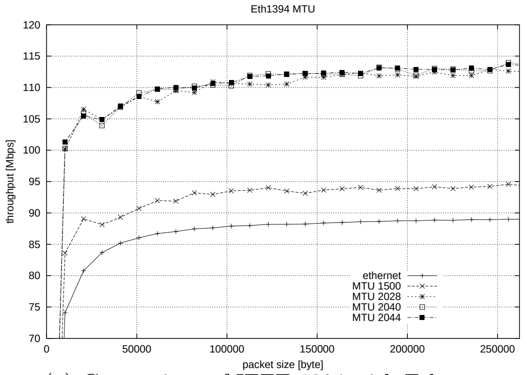
Fig. 5. Implementation

TCP-1394 follows the standard flow control mechanism for the asynchronous non-real-time data. For the real-time data transmission, however, new flags defined in TCP-1394 header. TSP and ITM flags, in conjunction with *Time_Stamp* value are used for the flow control of real-time data. For the asynchronous real-time data with deadline, the sender tries to send data with setting TSP flag and storing deadline into Time_Stamp field. If it is successfully arrives, the receiver responds acknowledgement with setting ITM flag. If the transmission fails twice, the sender requests allocating bandwidth enough for the secure transmission to IRM. The timing sequence of real-time data transmission is shown in Fig. 4(a). For the isochronous data transmission, the sender allocates necessary bandwidth before the actual data transmission as shown in Fig. 4(b).

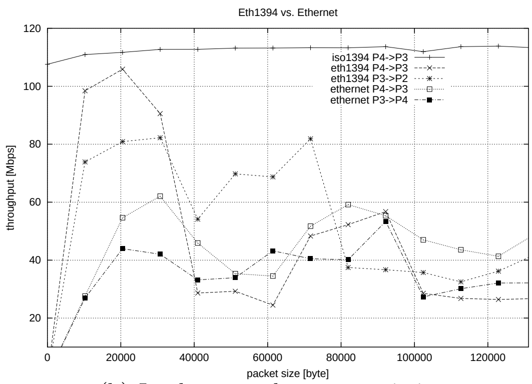
5. EXPERIMENT RESULTS

The performance of the proposed TCP/IP-1394 protocol is evaluated by experiments. Pentium-III computer with TI-TSB12V26, a widely used IEEE-1394 controller, and Linux operating system with standard IEEE-1394 device driver(Andersen, 1996) are used for the experiments. Fig. 5 shows the protocol stack implemented and used for the experiments. To measure network performance, Netpipe(Snell *et al.*, 1996; Turner *et al.*, 2003) and Etherreal(Ethereal, 2001) are used.

First, to compare the performance of IEEE-1394 bus and standard Ethernet, the performance of the asynchronous data transmission over IEEE-1394 bus and Ethernet is evaluated. Fig. 6(a) shows the throughput of Ethernet and IEEE-1394 bus when asynchronous data with varying packet size(MTU) are transmitted. From the experiments, IEEE-1394 bus shows much higher and stable throughput compare to Ethernet. Fig. 6(b) shows the performance of periodic data transmission using isochronous mode when they are mixed with asynchronous non-real-time data. While the throughput of asynchronous data fluctuates, IEEE-1394 bus has a stable performance for the real-time data using isochronous mode.



(a) Comparison of IEEE-1394 with Ethernet



(b) Isochronous data transmission

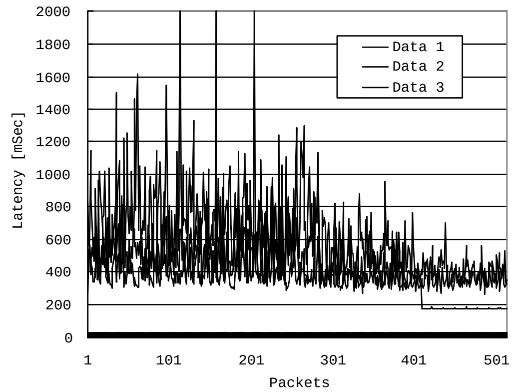
Fig. 6. Performance of IEEE-1394

Fig. 7(a) shows the actual transmission time for the periodic real-time data when normal TCP/IP with Ethernet is used. Although these data are supposed to be transmitted periodically, the actual transmission time varies a lot. The distribution of transmission time is depicted in Fig. 7(b). The experiment result shows that normal TCP/IP with Ethernet can not transfer periodic data successfully.

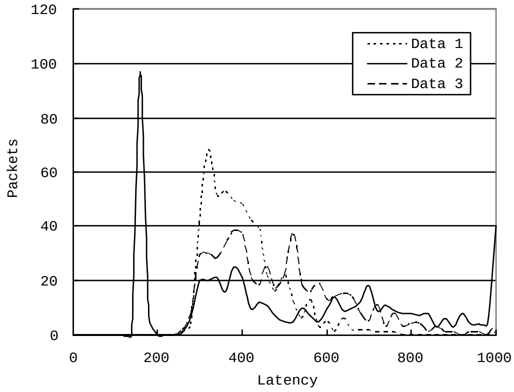
Fig. 7(c) and Fig. 7(d) show the actual transmission time of TCP/IP-1394 over IEEE 1394 bus and its distribution, respectively. One set of real-time packets and three sets of non-real-time packets are used for the experiments. Each set of data consists of 512 packets and each packet is transmitted periodically at every 100 *msec*. Compare to that of normal TCP/IP over Ethernet, the transmission latency remains within a short range. The experiment shows that for the real-time data with 100msec deadline , the maximum latency is 83.509msec and its average value and standard deviation are 81.034 and 0.0808, respectively. This means the proposed protocol guarantees the real-time performance for the real-time data transmission.

6. CONCLUSIONS

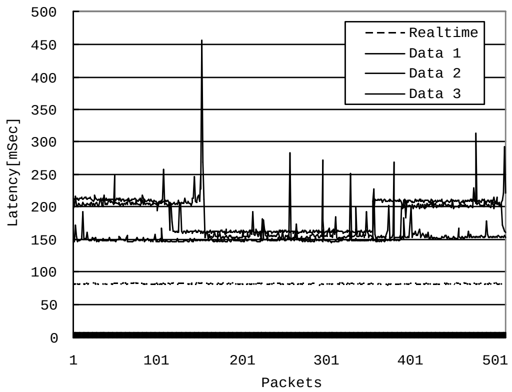
This paper proposes a modified TCP/IP protocol (TCP/IP-1394) for the real-time data transmission over IEEE-1394 serial bus. From the inher-



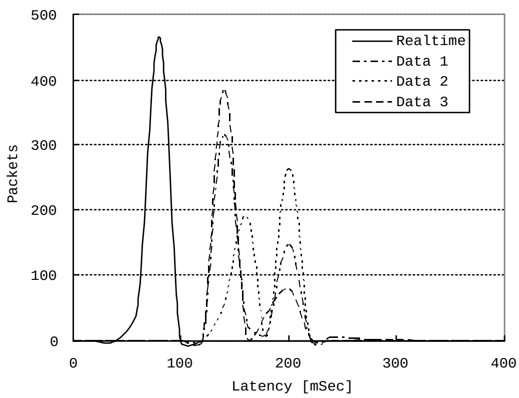
(a) Transmission time over Ethernet



(b) Latency distribution over Ethernet



(c) Transmission time over IEEE-1394



(d) Latency distribution over IEEE-1394

Fig. 7. Comparison of Transmission Latency

ent characteristics of IEEE-1394 bus, a real-time network can be easily achieved as the control and/or sensory network for the distributed control systems. TCP/IP-1394 provides a real-time communication for the time critical data with preserving compatibility with standard TCP/IP data stream. The experiment result shows that real-time data could meet their deadline even bulky normal TCP/IP data are mixed with them. The proposed TCP/IP over IEEE-1394 model can be widely used for the real-time control applications including the home networking, intelligent robot, and general distributed control systems.

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