Key words: *Discrete-event simulation, computer networking, control systems.*

Discrete-Event/Continuous-Time Simulation of Distributed Data Communication and Control Systems

Asok Ray
Seung Ho Hong
Suk Lee

Mechanical Engineering Department
The Pennsylvania State University
University Park, PA 16802

Pius J. Egbelu

Industrial Engineering Department
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

The paper deals with combined discrete-event and continous-time simulation of distributed data communication and control system (DDCCS) networks for autonomous manufacturing plants, power and chemical plants, and advanced aircraft and spacecraft. The time-varying and (possibly) stochastic delays, introduced by the network, occur in addition to the usual sampling time delay in digital control systems.

The delay and throughput characteristics of the Society of Automotive Engineers (SAE) linear token bus, SAE token ring and MIL-STD-1553B protocols have been analyzed in view of the DDCCS network design requirements. Simulation results are presented to illustrate how the network-induced delays could degrade performance and stability of the controlled process.

1. INTRODUCTION

The requirements for a distributed data communication and control system (DDCCS) network may vary for specific applications such as those

TRANSACTIONS of The Society for Computer Simulation
ISSN 0740-6797/88$2.00 + .10

Volume 5, Number 1, pp. 71-85

in automated manufacturing processes, electric power and chemical plants, and advanced aircraft and spacecraft (Ray and Phoha 1987; Ordrey 1985; Ray 1988b; Ray 1988a; Ray 1987; Hopkins 1981; Ray, Harper and Lala 1984). Selection of appropriate network access protocol(s) is critical for real-time operations of the automatic control systems which, in addition to the sampling time delay, is subjected to the time-varying and possibly stochastic delays that are introduced by the communication network. The detrimental effects of these delays are aggravated by mis-synchronization between system components and loss of messages resulting from saturation of buffers at the terminals and data corruption by noise in the network medium. In general, the requirements for a DDCCS network include low data latency, high throughput, and high reliability and availability. Moreover, the chosen architecture should be flexible and adaptable to future evolution.

The objectives of this paper are: (1) to analyze and make a comparative evaluation of the performance of protocols in view of the requirements of DDCCS network by discrete-event simulation, and (2) to demonstrate, by combined discrete-event and continuous-time simulation, how time-varying network-induced delays can degrade the performance and stability of a real-time control system.

The paper is organized in five sections and one appendix. The rationale for selecting specific protocol(s) for DDCCS networks is discussed in Section 2. The simulation model for network performance evaluation is described in Section 3. The results of simulation experiments are presented in Section 4. Summary and conclusions of this work are given in Section 5. Definitions of pertinent network parameters and their significance are presented in Appendix A.

2. IDENTIFICATION OF CANDIDATE PROTOCOLS

Protocols based on asynchronous time division multiplexing (TDM) techniques (Stallings 1985; Bertsekas and Gallager 1987) are suitable for real-time DDCCS networks that are subject to a combination of periodic, aperoidic and bursty traffic. These protocols can be classified as: (1) Random Access (e.g., CSMA and CSMA/CD), (2) Distributed Controlled Access (e.g., token ring, token bus, and collision avoidance), and (3) Centralized Controlled Access (e.g., polling).

The random access protocols are particularly suitable for lightly loaded media with bursty traffic but may not exhibit stable data latency under medium to high traffic (Stallings 1985; Bertsekas and Gallager 1987) depending on the magnitude of the propagation delay relative to the message transmission time. On the other hand, controlled access protocols yield relatively smaller at high traffic, and are more stable. Therfore, controlled access protocols with ring and bus topologies are considered to be potential candidates for the DDCCS.

Two high-speed distributed controlled access protocols, namely SAE linear token bus (SAE, 1987) and SAE token ring (SAE, 1985) were chosen as the candidate protocols for the DDCCS network. Larger communication speed and less complexity form the rationale for selecting SAE protocols as opposed to IEEE 802 family protocols (IEEE Std 802.4 - 1985; IEEE Std 802.5 - 1985). The performance of the SAE linear token bus and token ring protocols were compared with that of MIL-STD-1553B (centralized controlled access) (MIL-STD-1553B 1980) which has been extensively used in distributed digital avionic systems of military aircraft (Hopkins *et. al* 1981; Ray, Harper, and Lala 1984). Detailed descriptions of protocols are given in individual standards.

3. SIMULATION MODEL DEVELOPMENT

Simulation is used as a tool for evaluating DDCCS network performance in conjunction with mathematical analysis (Kleinrock 1976). One of the major objectives of simulating the distributed data communication and control system (DDCCS) is the comparative evaluation of the network protocols using one or more models of the process control system. This was achieved by decomposing the DDCCS into two modular subsystems which are: (1) Discrete-event model of the network, and (2) Continuous-time model of process dynamics and discrete-time model of the controller. The structure of the combined discrete-event and continuous-time simulation model of a DDCCS network is illustrated in Figure 1.

The network subsystem model consists of two independent but interacting submodels: (1) Message generation submodel; and (2) Protocol submodel. The message generation submodel has an identical structure for all types of protocols and is driven by an external pool of messages that arrive at the network system either periodically or at random intervals of time. Similarly, the message lengths can be either constants or randomly distributed. When a new message arrives at the system from the external message generator, the message attributes are defined to establish the message identity in the following ways:

- Time of arrival — this is the instant at which the arrival of a message at the transmitter queue is recorded.
- The message information length (overhead not included).
- The source terminal, i.e., the terminal from which the message is generated.
- The destination terminal — this could be any terminal on the network other than the source terminal.
- The message priority if applicable.

The protocol submodel essentially represents the algorithm of the network access protocol under consideration. Different submodels, each of which identically enters the simulation program as a subroutine, have been developed for SAE linear token bus, SAE token ring, and MIL-STD-1553B protocols. Although internal algorithms of the individual protocol submodels are different, their interactions with

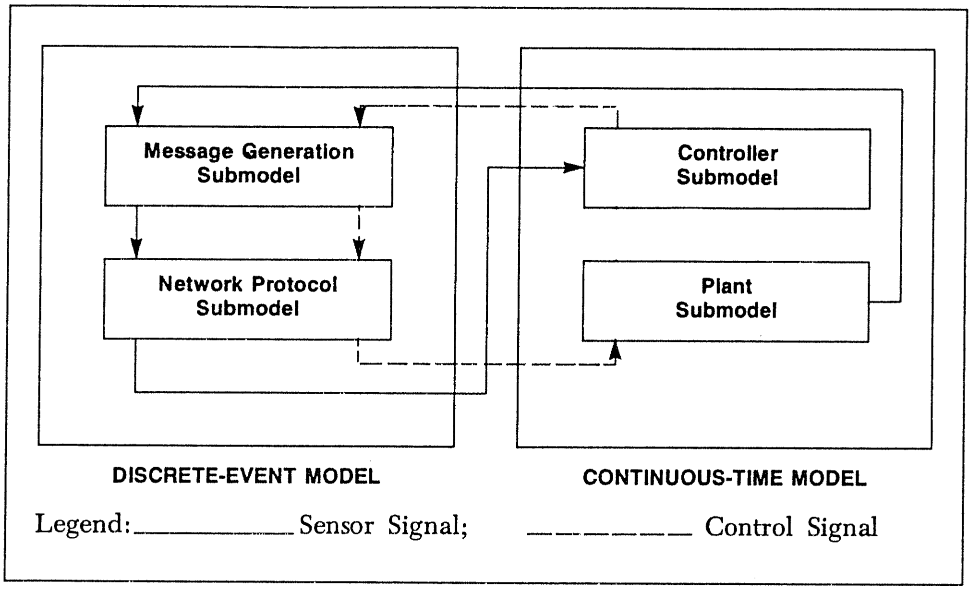

Figure 1: Simulation Program Structure for the DDCCS Network.

the message generation submodel and the plant and controller model are identical. The plant and controller models are formulated using the standard continuous-time and discrete-time state-variable approaches, respectively. The interactions between the plant and controller models involve exchange of sensor and control data which undergo time-varying delays introduced by scheduled events in the network model.

Key considerations in the choice of a language for the DDCCS network simulation were: (1) Combined discrete-event and continuous-time simulation capability; (2) Programming flexibility and software portability; (3) Verification and debugging capability; (4) Built-in statistical testing capability; and; (5) Automatic ordering of scheduled events.

4. MODEL EXPERIMENTATION VIA SIMULATION

Model experiments via simulation served the purpose of the DDCCS performance evaluation with respect to data latency and throughput. Figure 2 shows the structure of DDCCS. The following network configuration was employed as the basic model for simulation experiments and subsequent comparisons of the results.

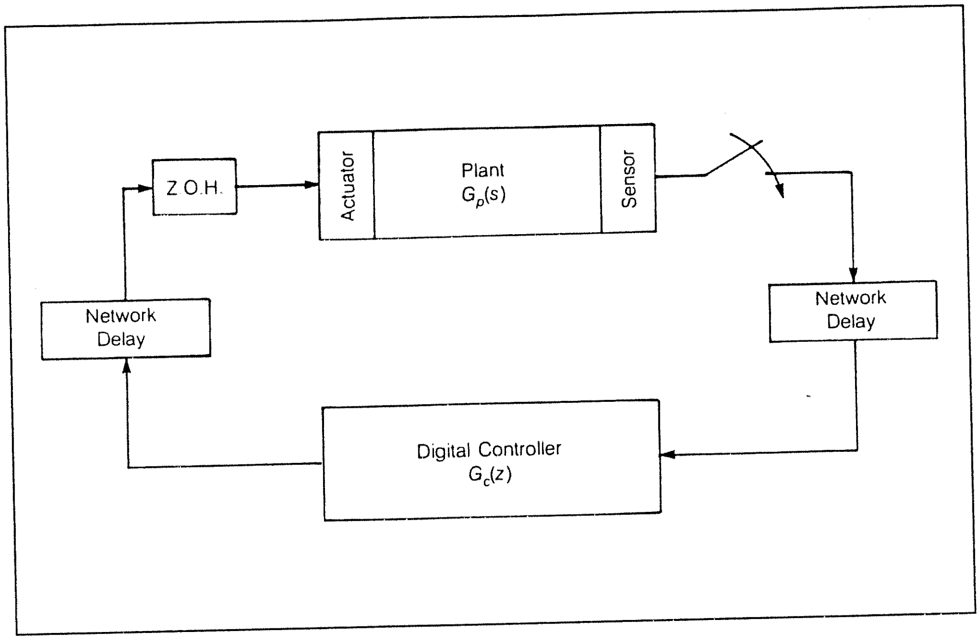

Figure 2. Schematic Diagram of the Closed Loop DDCCS.

- The network consists of 31 terminals or nodes (this is the upper limit for MIL-STD-1553B).
- Terminal #1 operates as the sensor and actuator terminal with its transmitter queue serving the sensor and its receiver queue serving the actuator.
- Terminal #2 operates as the controller terminal with its transmitter queue handling actuator commands and the receiver queue handling sensor data.
- Terminals #1 and #2 have periodic traffic with fixed-length messages with the data part $L = 32$ bits and a sample period of 10 msec.
- Terminals #3 to #31 are modelled as ordinary nodes of the network where the expected value of the message inter-arrival time was set to 10 msec and message lengths were varied to regulate the offered traffic in the network.
- The digital control system under consideration is single-input single-output with unity feedback. The plant transfer function was selected as $G_p(s) = 1/[(0.3s+1)\ (0.03s+1)]$ and the analog equivalence of the transfer function of the digital controller as $G_c(s) = 7(s+5)/s$ where s is the Laplace transform variable.

Steady-state performance evaluation of the DDCCS network was conducted under four different traffic scenarios based on message inter-arrival time T and data part L of message length: (1) Constant T and constant L, i.e., deterministic traffic; (2) Constant T and exponentially distributed L; (3) Exponentially distributed T and constant L; and (4) Both T and L being exponentially distributed.

4.1 Network Analysis Under Deterministic Traffic

Each protocol was simulated at two values of queue limits: $Q = 1$ and $Q = 2$, and three values of offered traffic: $G = 0.2$, $G = 0.7$ and $G = 1.2$. (See Definitions in Appendix A). The critical offered traffic G_{cr} for $N = 31$ and $T = 10$ msec was computed to be 0.993, 0.986 and 0.523 for SAE token bus, SAE token ring, and MIL-STD-1553B, respectively (Ray 1987). Table 1 provides the steady-state results for average data latency and throughput under six different combinations of queue capacity and offered traffic for each protocol. Since the traffic is deterministic only one replication per combination was necessary.

Table 1.
Comparison of Protocol Performances (Fixed T and Fixed L).

Average Data Latency (μsec)

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G = 0.2$	$G = 0.7$	$G = 1.2$	$G = 0.2$	$G = 0.7$	$G = 1.2$	$G = 0.2$	$G = 0.7$	$G = 1.2$
$Q = 1$	3231	5308	5508	1077	3659	5404	1116	3690	5407
$Q = 2$	3231	15309	15508	1077	3659	15404	1116	3690	15407

Throughput

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G = 0.2$	$G = 0.7$	$G = 1.2$	$G = 0.2$	$G = 0.7$	$G = 1.2$	$G = 0.2$	$G = 0.7$	$G = 1.2$
$Q = 1$	0.200	0.579	0.649	0.200	0.700	0.996	0.200	0.700	0.991
$Q = 2$	0.200	0.579	0.649	0.200	0.700	0.996	0.200	0.700	0.991

Results indicate that the linear token bus and token ring protocols clearly excel MIL-STD-1553B in terms of data latency. The reason for the relatively poor performance of MIL-STD is its longer bus idle time and larger overhead due to its message formatting structure. The linear token bus yields a slightly better performance than the token ring but the difference may not be of statistical significance. The data latency is a monotonically increasing function of offered traffic G and bears a direct relationship to the queue limit only if $G > G_{cr}$. The analytical model results in (Ray 1988a; Ray 1987) are in agreement with the simulation results.

In terms of throughput, the performance of all three protocols are identical for $G = 0.2$ which is less than their critical offered traffic G_{cr}. However, for $G = 0.7$, MIL-STD exceeds its critical value and loses some of its messages whereas the other two protocols do not. At $G = 1.2$, all protocols exceed their G_{cr} and therefore suffer from message rejection. Since MIL-STD has a much smaller G_{cr} than the others, it has a smaller throughput.

The steady-state performance data, i.e., the average values, in Table 1 are significant from a network design point of view. However, for control system design, the time-varying charactersitics of the data latency need to be taken into account. The average data latency and throughput or any other steady state statistical data such as standard deviation do not provide sufficient information for the network dynamics.

The effects of time-varying delays on the performance and stability of a feedback control loop in the DDCCS network were demonstrated by experiments on the simulation model. The results of the closed loop simulation of the DDCCS are presented as a series of curves in Figure 3 illustrating the transient responses of the plant output for a unit step increase in the reference input from an initial steady state condition. Since the queuing delay and throughput characteristics of SAE token ring and linear token bus are similar to a large extent, the transient responses of the DDCCS were generated with the SAE linear token bus and MIL-STD-1553B as network access protocols. Transient responses under identical conditions were obtained for an equivalent centralized digital controller, i.e., without a network, where the control loop is not subject to any delay except the usual sampling time delay. These responses were used as a reference in Figure 3 for evaluating the performance of individual protocols in the DDCCS network.

Figure 3a shows transient responses for $G = 0.2$. Since G is less than G_{cr} for both protocols, data latency is independent of the queue limit, and thus the transient responses for $Q = 1$ and $Q = 2$ are identical for each protocol. The response

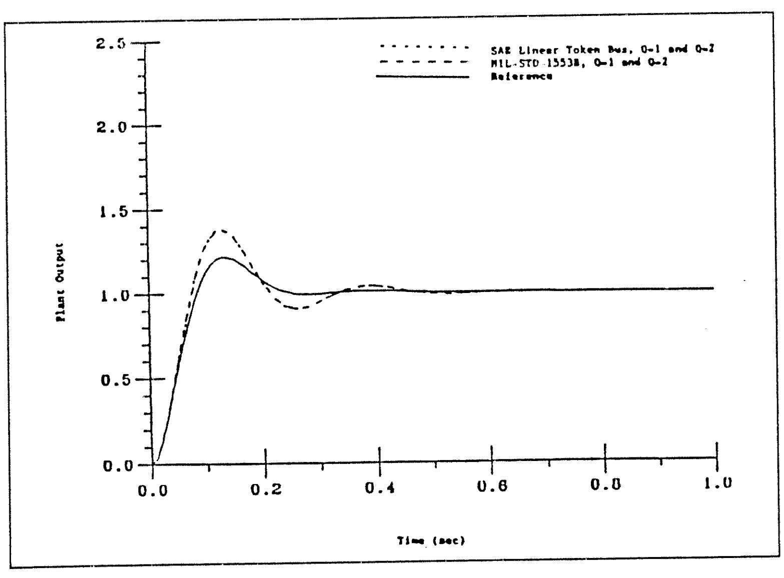

Figure 3a. Transient Response of Plant Output at $G = 0.2$.

of the plant output is almost identical for both protocols although there is a noticeable degradation with respect to the reference response obtained from an equivalent centralized control system. This is an evidence of the additional delay contributed by the network access protocols.

The transient responses for $G = 0.7$ are given in Figure 3b. The performance of MIL-STD-1553B for $Q = 1$ is changed to some extent with respect to that for $G = 0.2$ in Figure 3a since G exceeds G_{cr} only for MIL-STD-1553B which has a larger overhead and idle time than the linear token bus discussed earlier. For MIL-STD-1553B, some messages are lost due to queue stauration. If Q is set to 2 for MIL-STD-1553B, the steady-state data latency at each terminal is increased by an additional amount of one sample time. In this case the dynamic response of plant output becomes much worse due to the increased delays. For the linear token bus, since G is still smaller than G_{cr}, the DDCCS does not suffer from loss of messages due to queue saturation and additional delays, and thus exhibits much superior performance.

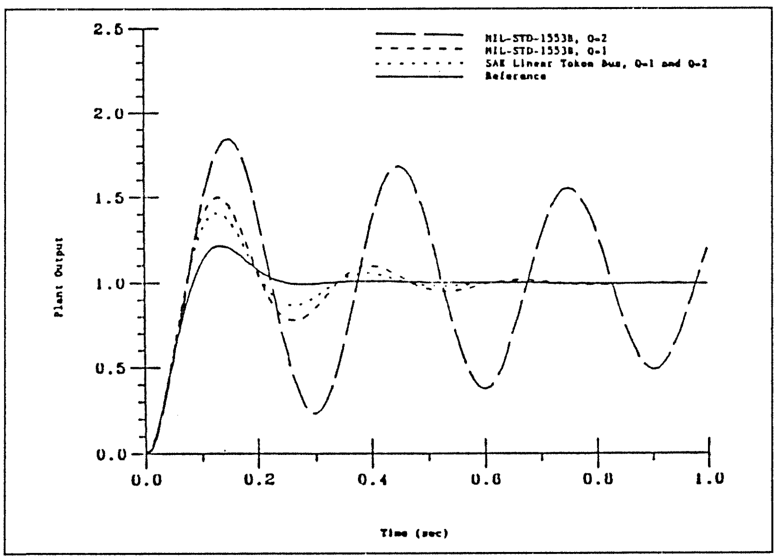

Figure 3b. Transient Response of Plant Output at $G = 0.7$.

Figure 3c shows transient responses for $G = 1.2$ where G exceeds G_{cr} for both protocols. For $Q = 1$, MIL-STD-1553B suffers from a long settling time whereas the performance of token bus is not seriously degraded. However, for $Q = 2$ both protocols suffer from increased data latency as a result of the additional data latency and exhibit instablilty of the control system. Performance and stability of the DDCCS are much better for queue limit of 1 than for larger queue limits for all protocols whenever G exceeds G_{cr} .

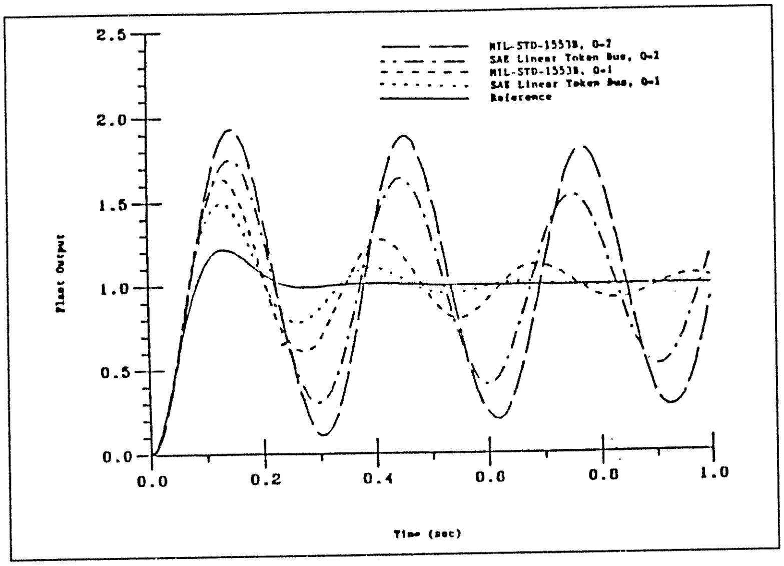

Figure 3c. Transient Response of Plant Output at $G = 1.2$.

The above observations are generic in nature and are applicable to DDCCS networks for power and chemical plants, autonomous manufacturing processes, and aircraft. Although the process dynamics in different applications may vary widely, the concept of dimensionless offered traffic and the resulting delays relative to the sampling period is similar in all cases.

4.2. Network Analysis Under Stochastic Traffic

The previous analysis was based on deterministic traffic, i.e., constant inter-arrival time T and message length L. In many applications such as routine information exchange between design office and factory floor in an autonomous manufacturing environment, T and/or L are random variables. With no detailed discussions provided for the sake of conciseness, the simulation results for different combinations of constant and exponentially distributed cases of T and L are listed in Tables 2, 3, and 4. Offered traffic G is obtained on the basis of expected values of message inter-arrival time and message length. In each case the expected value of T was chosen to be 10 msec and that of L for each of the terminals #3 to #31 was computed on the basis of a given G. In each case the arrival process was Poisson, and T and L were independent. Each Table entry is based on an average result of three replications.

Based on the simulation results provided in Tables 1 to 4, the following inferences are made.

Table 2.
Comparison of Protocol Performances (Fixed T and Random L)

1. Average Data Latency (μsec)

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$
$Q=1$	3101	5258	5477	1079	3687	5338	1123	3714	5334
$Q=2$	3101	15240	15482	1079	3708	15178	1123	3738	15228

2. Throughput

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$
$Q=1$	0.200	0.581	0.642	0.200	0.700	0.996	0.200	0.700	0.992
$Q=2$	0.200	0.584	0.641	0.200	0.700	0.995	0.200	0.700	0.991

Table 3.
Comparison of Protocol Performances (Random T and Fixed L)

1. Average Data Latency (μsec)

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$
$Q=1$	2095	3842	6206	110	499	2338	127	508	2356
$Q=2$	3367	9393	15555	110	567	7684	127	577	7720

2. Throughput

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$
$Q=1$	0.162	0.576	0.629	0.200	0.681	0.996	0.200	0.682	0.992
$Q=2$	0.190	0.541	0.644	0.200	0.693	0.996	0.200	0.693	0.992

Table 4.
Comparison of Protocol Performances (Random T and Random L)

1. Average Data Latency (μsec)

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$
$Q=1$	2066	3807	5914	118	668	2500	135	676	2535
$Q=2$	3260	9189	15131	119	820	7899	136	835	8096

2. Throughput

	MIL-STD-1553B			SAE Linear Token Bus			SAE Token Ring		
	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$	$G=0.2$	$G=0.7$	$G=1.2$
$Q=1$	0.163	0.527	0.632	0.200	0.673	0.996	0.200	0.674	0.991
$Q=2$	0.191	0.526	0.635	0.200	0.696	0.996	0.200	0.696	0.992

- For all protocols with $G<G_{cr}$, average queuing delay and data latency are improved with larger variability in traffic. Randomness of T contributes more to performance improvement than that of L. However, no general conclusion can be drawn for $G>G_{cr}$ and especially if G is significantly larger than G_{cr}.
- As G exceeds G_{cr}, the throughput converges to a limit which is unique for each protocol. Traffic variability does not significantly influence the throughput even at high G.
- SAE linear token bus and token ring protocols yield almost equivalent performance which is superior to that of MIL-STD.
- Based on the average data latency, SAE linear token bus and token ring exhibit their best performance under Poisson arrival of messages with constant lengths. Their throughput performance need not significantly deteriorate with traffic variability.

5. SUMMARY AND CONCLUSIONS

The performance of the SAE linear token bus, SAE token ring and MIL-STD-1553B protocols has been analyzed in view of the requirements for real-time distributed data communication and control system (DDCCS) networks. Performance evaluation was carried out using a simulation model which agreed with the results derived from analytical models. The simulation results were generated to demonstrate how the time-varying delays introduced in network access protocols can degrade the dynamic performance of the controlled process.

For future research, the priority scheme of the token bus protocol should be investigated to accommodate traffic in multiloop control systems with different sampling frequencies (Jayasumana 1987). In addition, an enhanced simulation technique such as perturbation analysis could be applied to for more efficient modelling of DDCCS networks (Ho 1987).

ACKNOWLEDGEMENTS

This work was supported in part by Bendix Flight Systems Division of Allied Signal Corporation, Teterboro, NJ under the research contract #81-547792.

REFERENCES

Bertsekas, D. and Gallager, R., 1987. *Data Networks*, Prentice Hall, Englewood Cliffs, NJ.

Ho, Y.C., July 1987. "Performance Evaluation and Perturbation Analysis of Discrete-Event Dynamic Systems," *IEEE Trans. on Automatic Control*, Vol. AC-32, No. 7, pp. 563-572.

Hopkins, A.L., et al, June 1981. "System Data Communication Structures for Active-Control Transport Aircraft," Volume II, NASA Report CR 165774.

IEEE Std 802.4, 1985. Token Passing Bus Access Method and Physical Layer Specifications.

IEEE Std 802.5, 1985. Token Ring Access Method and Physical Layer Specifications.

Jayasumana, A.P., March 1987. "Performance Analysis of a Token Bus Priority Scheme," *IEEE INFOCOM*.

Kleinrock, L., 1976. *Queueing Systems, Volume II: Computer Applications*, Wiley, New York.

Ordrey, N.G., 1985. *Integrating the Automated Factory, Data Processing Management*, Auerbach Publishers, Inc.

Protocol Manual, February 1980. MIL-STD-1553B. United States Government Printing Office.

Ray, A., Harper, R., and Lala, J.H., February 1984. "Damage-Tolerant Multiplex Bus Concepts for Far-Term Digital Flight Control Systems," Draper Laboratory Report CSDL-R-1690.

Ray, A. and Phoha, S. (eds.), 1987. *Proceedings of the Workshop on Computer Networking for Manufacturing Systems*, National Science Foundation, November 4-6, held at Penn State University.

Ray, A., December 1987. "Performance Evaluation of Medium Access Control Protocols for Distributed Digital Avionics," *ASME Journal of Dynamic Systems, Measurement and Control*, pp. 370-377.

Ray, A., March 1988a. "Distributed Data Communication Networks for Real-Time Process Control," *Chemical Engineering Communications*, Vol. 65, pp. 139-154.

Ray, A., May 1988b. "Networking for Computer-Integrated Manufacturing," *IEEE Network Magazine: Special Issue on Communications for Manufacturing*, Vol. 2, No. 3, pp. 40-47.

SAE, May 1987. Linear Token Passing Multiplex Data Bus. AS4074.1, Version 3.0.

SAE, November 1985. High Speed Ring Bus Standard. Issue 1.

Stallings, W., 1985. *Data and Computer Communications*, Macmillan Publishing Company, New York.

Date received: August 1986, date accepted: March 1988.

APPENDIX A: NETWORK PARAMETERS DEFINITIONS AND CONCEPTS

The key parameters for performance evaluation of communication network protocols in real-time distributed control environment are: (1) network reliability and system availability, and (2) data latency and data throughput. Reliability and availability are largely hardware-dependent and are usually analyzed during the hardware design phase when detailed specifications become available. Undetected data frame errors may affect the system reliability although detected errors which are usually in the order of 10^{-12} to 10^{-8}, have no significant bearing on network performance parameters.

Data latency and throughput are dependent on traffic pattern which, in turn, are governed by message arrival rate, time sequence of message arrival and transmission on the network medium, message length, buffer size at individual terminal's queues, and number of terminals in the network. Definitions of DDCCS network performance parameters are introduced below.

Definition 1. Queueing delay δ_q of a successfully transmitted message is the difference between the instant of arrival of the message at the transmitter queue of the source terminal and the instant of transmission of its first bit on the medium.

Definition 2. Data latency δ of a successfully transmitted message is defined as the difference between the instant of arrival of the message at the transmitter queue of the source terminal and the instant of reception of its last bit at the destination terminal.

Definition 3. Offered traffic G is defined as:

$$G = \sum_{i=1}^{N} (E[L_i] \,/\, (R E[T_i]))$$

where L = length of the data part of a message (bits)
N = number of active terminals in the network
R = medium bandwidth (bits/sec),
T = message inter-arrival time at a terminal (sec),
$E[*]$ denotes the expected value of *, and the subscript i denotes the terminal #i.

Remark 1. For a given G, individual protocols may load the medium to different levels and thus influence the performance of the DDCCS to different degrees. Therefore, a limit of G above which a given protocol is expected to overload the medium, resulting in message rejection, needs to be specified.

Definition 4. For a given protocol, the critical offered traffic G_{cr} is defined as the largest offered traffic for which, assuming infinite saturation limits, all queues are bounded saturation for deterministic traffic under steady state.

Definition 5. Throughput S is defined as the ratio of the average rate of the data bits transmitted through the medium under steady state and the medium bandwidth.

In a feedback control loop, messages are transmitted via the network medium from the sensor terminal to the controller terminal and from the controller terminal to the actuator terminal. Thus the control system is subject to time-varying delays due to data latency, and its performance is dependent on the traffic in the network. Additional definitions of pertinent parameters are introduced in this regard.

Definition 6. Sensor-controller delay Θ_{sc} is defined as the difference between the instant of arrival of the sensor data at the transmitter queue of the sensor terminal and the instant at which the controller starts processing the same data.

Remark 2. The sensor data should wait at the receiver buffer of the controller terminal until the controller sampling instant.

Remark 3. If the sensor and controller have the same sampling time T, then Θ_{sc} can be expressed in terms of the sensor-controller data latency δ_{sc} and the skew Δ_s between the sensor and controller sampling instants as:

$$\Theta_{sc} = \Delta_s \text{ for } \delta_{sc} < \Delta_s \text{ and}$$

$$\Theta_{sc} = kT + \Delta_s \text{ for } (k-1)\, T + \Delta_s \leqslant \delta_{sc} < kT + \Delta_s, \text{ for } k \text{ is a positive integer.}$$

Definition 7. Controller-actuator delay Θ_{ca} is defined as the sum of controller-actuator data latency and the processing delay at the controller.

Remark 4. There is no waiting time at the actuator terminal, i.e., the control signal acts upon the plant as soon as it arrives at the actuator terminal.

Remark 5. Sources of time delay in the DDCCS loop are:

- Delays associated with Θ_{sc} and Θ_{ca}.
- Additional delay contributed by rejected messages due to queue saturation and detected frame errors.
- Usual delay due to sampling time in digital control systems.

Asok Ray holds a Ph.D. degree in Mechanical Engineering (Northeastern University, 1976) and a Master's degree in Electrical Engineering, Computer Science, and Mathematics. Dr. Ray has about fifteen years of research and management experience at GTE Strategic Systems Division, Charles Stark Draper Laboratory, and MITRE Corporation. He has also held research and academic positions at Carnegie-Mellon University and Massachusetts Institute of Technology. Dr. Ray joined the faculty of Mechanical Engineering at Pennsylvania State University as an Associate Professor in July of 1985.

Dr. Ray's research experience includes real-time microcomputer-based distributed control instrumentation, networking and communication protocols, intelligent systems design, and modelling and simulation of dynamical systems as applied to avionics, process control, and autonomous manufacturing. Current research interests of Dr. Ray include distributed control systems for aircraft and spacecraft, knowledge-based expert systems for computer-integrated manufacturing, and computer communication networks.

Dr. Ray has authored or co-authored over one hundred research publications, and is a Senior Member of IEEE and a member of ASME.

Seung Ho Hong was born in Seoul, Korea. He received his B.S. degree in Mechanical Engineering from Yonsei University, Korea, in 1982, and his M.S. degree in Mechanical Engineering from the Texas Tech University, Lubbock, Texas, in 1985. He is currently a Doctoral Candidate in Mechanical Engineering at the Pennsylvania State University. His research interests include simulation of discrete-event systems, performance analysis of computer communication networks for aircraft control and computer-integrated manufacturing, and control system analysis and optimization. Mr. Hong is a member of Tau Beta Pi.

Suk Lee was born in Seoul, Korea. He received his B.S. degree in Mechanical Engineering from Seoul National University, Korea, in 1984, and his M.S. degree in Mechanical Engineering from the Pennsylvania State University, in 1986. He is currently a Doctoral Candidiate in Mechanical Engineering at Pennsylvania State University. His research interests include simulation and performance analysis of discrete-event systems, local area network management, communication networks for computer-integrated manufacturing, and distributed control systems.

Pius J. Egbelu received his M.S. and Ph.D. degrees in Industrial Engineering from Virginia Polytechnic Institute. Dr. Egbelu joined the faculty of Industrial and Management Systems Engineering at the Pennsylvania State University in 1984 as an Assistant Professor. His research interest include discrete-event simulation, production engineering, and computer networking.