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Performance Evaluation of Medium Access Control Protocols for Distributed Digital Avionics[1]

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The paper presents the results of an ongoing research project where the objectives are to evaluate medium access control (MAC) protocols in view of the requirements for distributed digital flight control systems (DDFCS) of advanced aircraft and to recommend a specific protocol for their prototype development. The selection of an appropriate MAC protocol is critical for the dynamic performance of an aircraft because the DDFCS, in addition to the sampling time delay, is subject to time-varying transport delays due to data latency of messages at different terminals of the control loop. The SAE linear token bus, SAE token ring and the conventional MIL-STD-1553B protocols have been analyzed using combined discrete-event and continuous-time simulation techniques. The impact of data latency on the dynamic performance of an advanced aircraft is illustrated by simulation of the closed loop DDFCS.

1 Introduction

An advanced aircraft requires distributed information processing with a number of spatially dispersed digital computers to perform, in real time, a set of diverse but interrelated functions. These functions may range from fly-by-wire (or fly-by-light) active control to routine maintenance support [1]. The performance of the communication network, specifically data latency of messages, could be significantly influenced by the intensity and distribution of the network traffic. This has a major bearing on the dynamic performance of the distributed digital flight control system (DDFCS) which, in addition to the sampling time delay, is subject to the time-varying transport delays due to data latency of messages in the communication network [2, 3, 4]. The detrimental effects of data latency are aggravated by mis-synchronism between system components, and loss of messages resulting from saturation of buffers at the terminals and noise corruption in the network medium. In general, the requirements for a DDFCS network include low data latency, high throughput, and high reliability and availability. Moreover, the chosen protocol should be flexible and adaptable to future evolution in the sense that the flight management functions can be continually modified and augmented in time along with updating of the software and hardware of the DDFCS.

In view of the above considerations the selection of a medium access control (MAC) protocol plays a critical role in the design and development of the DDFCS network. The performance of the candidate protocols should be systematically evaluated to identify a specific protocol for the development of a prototype DDFCS. This requires interactions between the disciplines of communication systems and control systems engineering.

The objectives of this paper are (1) to evaluate the performance, primarily data latency, of medium access control (MAC) protocols which are potential candidates for use in real-time DDFCS networks, and (2) to show how the time-varying transport delays due to data latency in MAC protocols can degrade the dynamic performance of the DDFCS.

The paper is organized into five sections and three appendices. The rationale for selecting SAE linear token bus and SAE token ring as candidate protocols is given in Section 2. The performance analysis of the protocols is addressed in Section 3. The results of a DDFCS network simulation along with the structure and scenarios for the simulation program are discussed in Section 4. The summary and conclusions of this research are presented in Section 5. Appendix A contains the models of the airframe dynamics and the flight controller of the aircraft under consideration. The structure and salient features of the combined discrete-event continuous-time simulation program are briefly decribed in Appendix B. Examples for calculating critical offered traffic are illustrated in Appendix C.

2 Identification of Candidate Protocols

Protocols based on asynchronous time-division multiplexing (TDM) are suitable for a DDFCS because the traffic is periodic as well as bursty. The widely-used asynchronous TDM techniques [5] can be classified for bus and ring topologies as: Distributed Controlled Access (e.g., token bus

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Table 1 Comparison of medium access protocols

Features	SAE linear token bus	SAE token ring	MIL-STD-1553B (command/response)
Type of medium access	Distributed	Distributed	Centralized
Transmission rate (Mbits/s)	50	40	1
Data word length (bits)	16	16	16
Formatted word length (bits)	16	16	20
Maximum # of terminals	128	128	31
Maximum meassage size (# of word counts)	4096	4096	32
Message Overhead (bits)	84	132	40 or 80
Message/token holding delay (μs)	0.5	1	--
Response time (μs)	--	--	12
Intermessage gap (μs)	--	--	4

and token ring), Centralized Controlled Access (e.g., polling as used in MIL-STD-1553B), and Random Access (e.g., CSMA and CSMA/CD).

The random access protocols like CSMA and CSMA/CD are particularly suitable for lightly loaded networks with bursty traffic but may not exhibit stable data latency under medium to high traffic [5] depending on the magnitude of the propagation delay relative to the message transmission time. On the other hand, controlled access protocols yield relatively larger data latency at light traffic and smaller at high traffic, and are more stable. In view of dynamic performance of the DDFCS, large data latency (on the order of the sample time) at high traffic is of serious concern whereas small data latency (on the order of small fractions of the sample time) at light traffic is of no major importance. Therefore, controlled access protocols with ring and bus topologies were considered to be potential candidates for the DDFCS.

Hybrid protocols like BRAM [6], CSMA/CD-DP [7], and CSMA/CD-DCR [8] that combine many features and advantages of both random access and distributed controlled access classes have been investigated. Although these novel protocols are reaching technological maturity and some of them are already commercially available (UniLink protocol of Applitek Inc. for example), they have not yet been thoroughly tested and, therefore, were not considered for avionic applications.

Two high-speed distributed controlled access protocols, namely SAE linear token bus [9] and SAE token ring [10] have been chosen as the candidate protocols for the DDFCS network. The performance of linear token bus and token ring protocols were compared with MIL-STD-1553B protocol [11] which has been extensively used in digital avionic systems of military aircraft. Table 1 summarizes the features of these three protocols, that are pertinent to the performance analysis of the DDFCS.

SAE token ring protocol has a physical ring structure to which terminals are attached. A token circulates freely on the ring in one direction while no terminal has a waiting message. A terminal with a ready message may transmit the message after capturing the token on the ring. After completion of a message transmission, the token is released on the ring. The next terminal downstream with a ready message captures the token and the same procedure is repeated.

SAE linear token bus is conceptually similar to SAE token ring although the physical phenomena of the message/token bit transmission are entirely different. The procedure for controlling access to the bus is, to some extent, identical to that of SAE token ring [9, 10]. In the token bus protocol, the terminals on the bus form a logical ring around which the token circulates. Under normal operating conditions, the token ring and token bus protocols have similar characteristics of data latency and throughput.

MIL-STD-1553B is a centralized controlled access protocol with the bus topology. One terminal is designated as bus controller and messages are exchanged through this controlling terminal. There are two major modes of operations for the bus controller: (1) Command/response mode which always requires an acknowledgement in the form of a status word from the addressed remote terminals, and (2) Broadcast mode which uses a common address and an acknowledgement is not solicited. The protocol may also operate in the dynamic bus control mode in which the bus controller may dynamically reassign the control functions to another terminal. Only the command/response mode of MIL-STD-1553B has been compared with linear token bus and token ring.

3 Protocol Performance Evaluation

The key parameters [1] for performance evaluation of communication network protocols in real-time distributed digital flight control environment are (1) data latency (i.e., the time delay encountered in accessing the network medium as well as for serial transmission of message bits), (2) data frame error rates (detected and undetected), and (3) network reliability and system availability.

Reliability and availability are largely hardware-dependent and are usually analyzed during the hardware design phase when detailed specifications become available. Data frame error rate depends on the raw bit error rate (on the order of 10**-12 to 10**-8 [5]) in the network medium and the error detection algorithm provided in the protocol (e.g., 16-bit cyclic redundancy check in SAE linear token bus). Although occassional message retransmissions or rejections as a result of detected frame errors have no significant bearing on the average data latency, it is the undetected frame errors that degrade control system reliability. Therefore, the issue of undetected frame error rate should be dealt along with reliability.

3.1 Protocol Modelling and Network Performance Analysis. The following operating conditions were assumed for modelling the DDFCS network protocols.

- Each terminal has one transmitter queue and one receiver queue.
- Message interarrival time at each terminal of the network is identical and constant. (This is effectively the sampling interval for the control system.)
- Message length at a given terminal is a constant. (Message lengths at different terminals may be different.)
- The clocks at individual terminals may or may not be snychronized.
- FIFO ranking is adopted at each terminal's transmitter queue and its buffer capacity is limited to an a priori assigned constant; in the event of queue saturation, the first message (i.e., the message at the front end of the queue) is rejected and the stack is pushed down to accommodate the new arrival.
- When a message is ready to be transmitted, it is transferred

from the transmitter queue to the output register and the process of transmission starts immediately. The message is cleared from the output register as soon as its transmission is complete.

The performance of a DDFCS network is dependent on the network traffic which is related to the characteristics of the control system and the MAC protocol. In this repect definitions of pertinent parameters relative to periodic traffic and constant message lengths are introduced below.

Definition 1. For a message, the word count w_c is defined as

$$w_c(L) = \begin{cases} \text{Int}\,(L/w_d) \text{ if } \text{Rem}(L,w_d) = 0, \\ \text{Int}\,(L/w_d) + 1 \text{ if } \text{Rem}(L,w_d) > 0. \end{cases}$$

where

L is the length (bits) of the information part of a message that arrives at the transmitter queue of a terminal (bits due to message formatting and overhead are excluded),
w_d is the number of bits per data word,
Int (*) indicates the integer part of *, and
Rem $(a,b) = a - [\text{Int}\,(a/b)]b$.

Definition 2. Frame length L' (bits) of message is defined as

$$L' = w_f w_c(L) + \Delta L$$

where

w_f is the length (bits) of a formatted word, and
ΔL is the length (bits) associated with the overhead of a message.

Definition 3. 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.

Definition 4. Data latency δ_l 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.

Remark 1. Neglecting the effect of propagation delay, queueing delay and data latency are related as

$$\delta_l = \delta_q + L'/R$$

where R is the data transmission rate in the network medium in bits/s.

Definition 5. Cycle time τ is defined as

$$\tau = N\sigma + \sum_{i=1}^{N} L'_i/R$$

where

N is the number of terminals in the network,
σ is the average bus idle time prior to the beginning of a message transmission, and
the subscript i corresponds to the terminal #i.

Remark 2. For a given traffic, cycle time may be interpreted as the total time required to complete the transmission of one message from each of the N terminals.

Remark 3. Under steady state conditions, messages are rejected due to queue saturation iff the cycle time exceeds sampling time T.

Definition 6. For a given traffic, the normalized cycle time, G' is defined as the ratio of the cycle time and the sampling interval, i.e., $G' = \tau/T$.

Definition 7. The offered traffic G is defined as

$$G = \sum_{i=1}^{N} L_i/(RT)$$

where L, N, R, T, and the subscript i are as defined above.

Remark 4. For a given G, individual protocols may load the network to different levels and thus influence the dynamic performance of the DDFCS to different degrees. Therefore, G is used as a parameter for selection of MAC protocols, and a limit of G above which a given protocol is expected to overload the network needs to be specified.

Definition 8. The critical offered traffic G_{cr}, for a protocol, is defined as the largest offered traffic for which no message frame is rejected due to queue saturation under steady state.

Remark 5. $G' \leq 1$ if $G = G_{cr}$.

For the closed loop DDFCS where messages are transmitted (via the network medium) from the sensor terminal to the controller terminal and from the controller terminal to the actuator terminal, additional definitions are introduced as follows.

Definition 9. Sensor-controller delay δ_{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 when the controller starts processing the same data.

Remark 6. If the sensor and controller have the same sampling time T, then δ_{sc} can be expressed in terms of the sensor-to-controller data latency δ_l and the time skew Δ_s between the sensor and controller sampling instants ($0 \leq \Delta_s < T$) as

$$\delta_{sc}(\delta_l, \Delta_s) = \begin{cases} \Delta_s \text{ for } \delta_l < \Delta_s \\ kT + \Delta_s \text{ for } (k-1)T + \Delta_s \leq \delta_l < kT + \Delta_s \end{cases}$$

where k is a positive integer.

Definition 10. Controller-actuator delay δ_{ca} is defined to be identically equal to the controller-to-actuator data latency.

Remark 7. 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 8. δ_{sc} and δ_{ca} are time-varying and, therefore, may not always be lumped together for stability analysis of the DDFCS.

Remark 9. Sources of the transport delay in the DDFCS loop are:

- Delays associated with δ_{sc} and δ_{ca}.
- The processing delay at the controller.
- Additional delay contributed by rejected messages due to queue saturation (see Section 3.1) and detected frame errors.
- Usual delay due to sampling in digital control systems.

3.2. Propositions. For periodic traffic with constant message lengths, the following propositions are presented below.

Proposition 1. Under steady state the number of messages waiting in the queue of each terminal is either 0 or 1 if $G \leq G_{cr}$, and either $(Q-1)$ or Q if $G > G_{cr}$, where the positive integer Q is the queue limit, i.e., the maximum number of messages that can wait at the queue of a terminal.

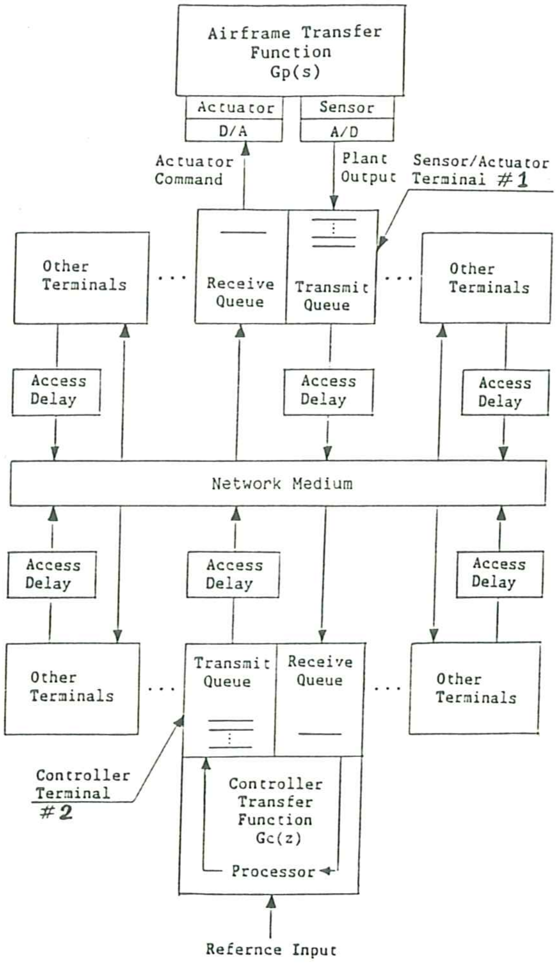

Fig. 1 Schematic diagram of the closed loop DDFCS

Proof of Proposition 1. For $G \leq G_{cr}$, none of the queues saturate because one message arrives at each terminal over a time interval of T and exactly one message is removed from each queue during the same time interval under steady state. The population of waiting messages at any queue under steady state never exceeds 1.

For $G > G_{cr}$, all queues saturate under steady state since one message always arrives at each terminal during a time interval of T but a terminal may not always have the opportunity to transmit a message during each interval of T. In this process the queue at each terminal will build up to the saturation limit Q and a message will be rejected whenever this limit exceeds. Therefore, starting from a point when the population at a queue is Q, at most one message is removed from the queue due to transmission during an interval of T and exactly one message arrives at the queue during the same time interval. Thus the population of waiting messages at each queue cannot be smaller than $(Q-1)$. ■

Proposition 2. The queueing delay under steady state is given as

$$\delta_q = \begin{cases} \delta_q^* & \text{for } G \leq G_{cr} \\ \delta_q^* + (Q-1)T & \text{for } G > G_{cr} \end{cases}$$

where δ_q^* is the queueing delay if $Q = 1$.

Proof of Proposition 2. For $G \leq G_{cr}$, the number of wating messages at each queue is at most 1. So, δ_q is independent of Q implying that $\delta_q = \delta_q^*$ for all Q.

For $G > G_{cr}$, by Proposition 1, the number of messages at each queue is either $(Q-1)$ or Q. Since a new message arrives at the queue at an interval of T and occupies a slot at the rear end of the queue. Therefore, every message will have to wait for a period equal to $(Q-1)T$ before it reaches the tip of the queue. Once it reaches the tip of the queue, the queueing delay is identical to that for $Q = 1$. ■

4 Results and Discussion

The effects of data latency in the DDFCS network on dynamic performance of an advanced aircraft were investigated by combined discrete-event and continuous-time simulation. A schematic diagram of the DDFCS network under consideration is shown in Fig. 1. The simulated plant model in Fig. 1 is of 3rd order representing the dynamics of the actuator and the airframe. Dynamic models of the plant and the flight controller are presented in Appendix A. Three sensor data of pitch rate, normal body acceleration and angle of attack are combined into one message and transmitted to the controller terminal through the network medium. Similarly the control signal message generated at the controller terminal is transmitted to the actuator.

Discrete-event models are suitable for representing the time-ordered sequences of operations that are encountered in MAC protocols. On the other hand continuous-time models are essential for solving the initial-value problems associated with the plant and controller dynamics. The coupling of two types of simulation permits the evaluation of the network as a dynamical element of the closed loop control system. This allows for monitoring the effects of delays introduced by the network.

The simulation program for evaluating the DDFCS performance was formulated with a modular structure with the following properties.

- Combined discrete-event and continuous-time simulation capabilities, and
- Flexibility for accomodating individual models of protocols, process dynamics and controller, and the supporting data base within the program structure.

The simulation program yields a numerical solution to the sets of linear time-invariant differential and difference equations which are interconnected by time-varying transport delays resulting from the MAC protocols. The linear models of the plant and controller in Appendix A can be replaced by nonlinear and time-variant models without having any structural changes in the simulation program. A brief description of the simulation program is presented in Appendix B.

Simulation results were generated under the following conditions: (1) there are 31 terminals (maximum limit in MIL-STD-1553B) that share the network medium, (2) traffic is periodic with a sampling period of 10 ms for all terminals, (3) terminal #1 operates as both sensor and actuator terminals with its transmitter queue serving the sensor and its receiver queue serving the actuator, (4) terminal #2 operates as the controller terminals with its transmitter queue handling actuator commands and its receiver queue handling sensor data, (5) terminals #1 and #2 have fixed message lengths with information part $L = 64$ bits, (6) every terminal except the controller simultaneously receives a message at the beginning of the sample, and (7) the terminals (#3 to #31) have identical message lengths. The message lengths for terminals #3 to #31 were varied to regulate the offered traffic G in the network. This approach was taken to assess the impact of traffic, generated by terminals which are included in the control loop, on the dynamic performance of the DDFCS.

The critical offered traffic G_{cr} for individual protocols can be computed on the basis of analytical relationships provided in Section 3.1 and using the data in Table 1. For the traffic scenario described in the previous paragraph, G_{cr} for the SAE linear token bus, token ring, and MIL-STD-1553B was com-

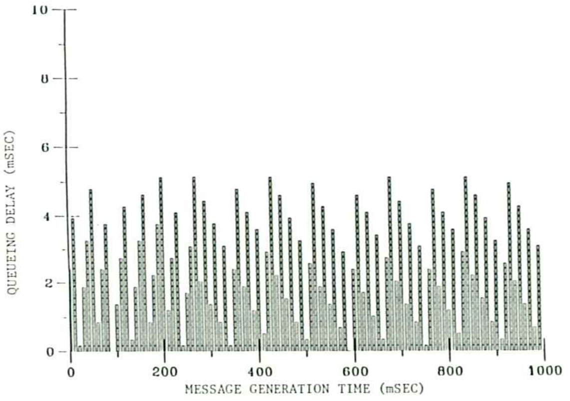

Fig. 2 Steady state profile of queueing delay for SAE linear token bus protocol

puted to be 0.993, 0.986, and 0.523, respectively. The procedure for calculating G_{cr} for these three protocols is shown in Appendix C.

Time history of queueing delay at individual terminals was recorded in the form of barcharts to investigate the time-varying nature of data latency. As an example, the queueing delay at the sensor/actuator terminal #1 under steady state periodic traffic is shown in Fig. 2 for SAE linear token bus at offered traffic $G=0.5$. The abscissa indicates the instants of time when the sensor data, as a message, arrives at the transmitter queue of terminal #1, and the ordinate indicates the queueing delay for these messages at terminal #1. For example, the message that arrives at the time instant 200 ms in Fig. 2 waits in the queue for about 5.25 ms before its transmission is initiated, i.e. its transmission starts at the time instant 205.25 ms.

Figure 2 indicates that the data latency could be time-varying even under steady-state periodic traffic with constant message lengths. Therefore, the conventional frequency domain analysis which is suitable for linear time-invariant systems may not be valid for analyzing the dynamic performance and stability of the closed loop DDFCS which is subject to time-varying transport delays. Time-domain techniques are needed to solve this problem analytically. This is a subject of current research.

Figures 3 to 5 illustate the transient response of the pitch rate for a unit step increase in the reference command input at the time instant of 0.5 sec from the zero initial condition under steady state network operations with offered traffic of 0.2, 0.7, and 1.2, respectively. Other plant variables such as body acceleration and angle of attack are not presented here due to space limitations. Since the data latency and throughput characteristics of SAE token ring and linear token bus are similar to a large extent for normal operations of the network, the simulations of SAE linear token bus and MIL-STD-1553B were generated. In order to assess the impact of protocols in the DDFCS performance, another curve for conventional control system with a centralized digital controller was generated as the reference in each figure.

Figure 3 shows transient response for $G=0.2$. Since G is less than G_{cr} for both protocols, data latency is independent of the queue limit Q by Proposition 2, and thus the transient responses for $Q=1$ and $Q=2$ are identical for each prtotocol in Fig. 3. The response of the pitch rate 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 transport delay contributed by the MAC protocols.

The transient responses for $G=0.7$ are given in Fig. 4. The performance of MIL-STD-1553B for $Q=1$ is changed to some extent with respect to that of $G=0.2$ in Fig. 3 since G exceeds G_{cr} only for the MIL-STD-1553B protocol which has a larger overhead and idle time than the linear token bus as discussed in Appendix C. Since $G>G_{cr}$, some messages are lost due to queue saturation for MIL-STD-1553B by Proposition 1. If Q is increased to 2 for MIL-STD-1553B, Proposition 2 states that the steady-state queueing delay at each terminal is increased by an additional amount of one sample time, i.e., 10 ms. In this case the dynamic response of pitch rate becomes

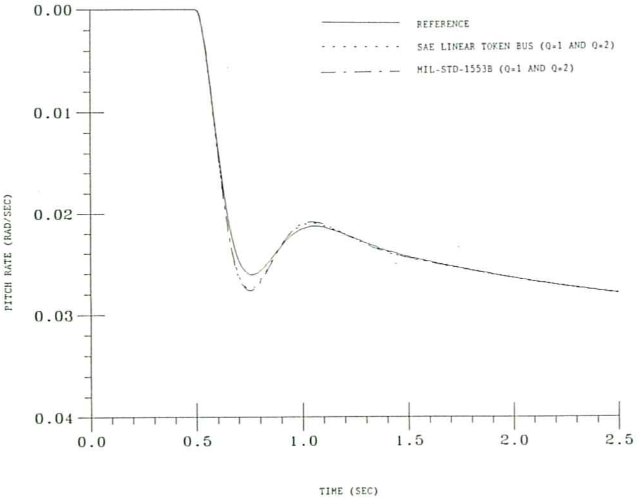

Fig. 3 Transient response of pitch rate for fixed traffic at $G=0.2$

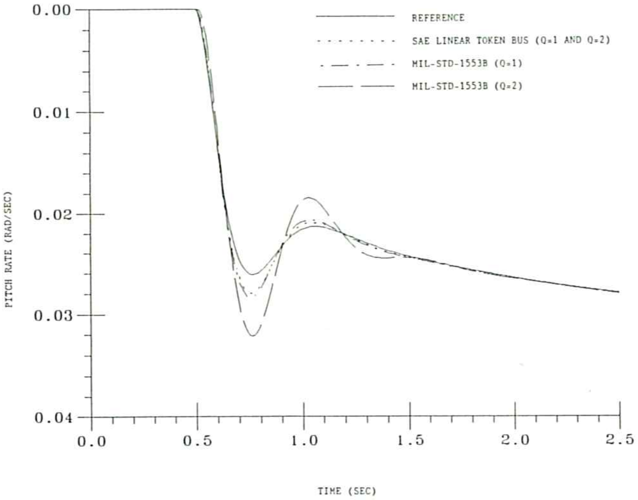

Fig. 4 Transient response of pitch rate for fixed traffic at $G=0.7$

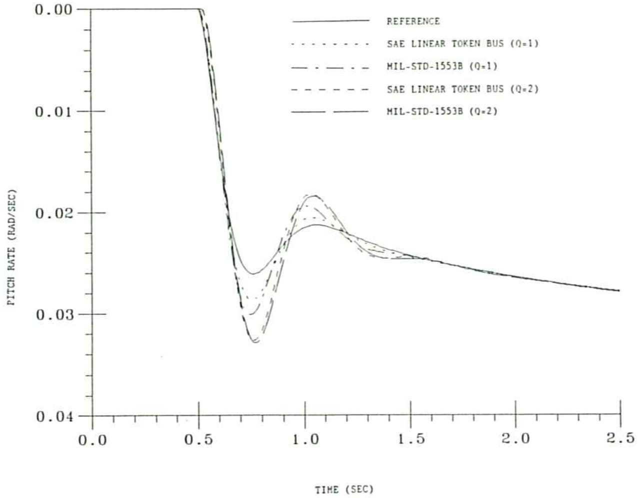

Fig. 5 Transient response of pitch rate for fixed traffic at $G=1.2$

much worse due to the increased data latency. For the linear token bus, as G is still smaller than G_{cr}, the DDFCS does not suffer from loss of messages due to queue saturation (and additional data latency), and thus exhibits much superior performance.

Figure 5 shows transient response for $G=1.2$ where G exceeds G_{cr} for both protocols. For $Q=1$ the performance of the linear token bus is noticeably better than that of MIL-STD-1553B because the latter protocol is subject to more frequent loss of messages due to queue saturation. However, for $Q=2$ both protocols suffer from increased data latency as a result of the additional queueing delay of 10 ms. At $Q=2$, the degradations in dynamic performance are comparable for linear token bus and MIL-STD-1553B.

Simulation results were also generated for random traffic with Poisson arrival and exponentially distributed message lengths in terminals #3 to #31 to investigate the effects of stochastic transport delays on the closed loop DDFCS. Dynamic responses for pitch rate, angle of attack, and body acceleration were obtained for $G=0.2$, 0.7, and 1.2 where G was computed on the basis of expected values of message interarrival time and message length. The transient responses for pitch rate were found to have characteristics similar to those in Figs. 3, 4, and 5. For $G<G_{cr}$, the transient responses with ramdom traffic were found to be practically indistinguishable from those for deterministic traffic with identical G (see Figs. 3 and 4) but similar conclusions could not be drawn for G in excess of its critical values when messages are more likely to be rejected due to queue saturation. These phenomena have not yet been analyzed but a possible explanation for a random traffic with small G is as follows.

A vast majority of the messages experience small queueing delays and only very few messages suffer from large queueing delays which could be treated as occasional disturbances. The plant and controller dynamics act as low pass filters to smooth these disturbances. Analytical evaluation of the effects of stochastic transport delays is a subject of future research.

Dynamic performance and stability are much better for queue limit of 1 than for larger queue limits for all protocols whenever G exceeds G_{cr}. If a terminal serves M devices that generate M different types of messages then the queue limit has to be set to M to accommodate for M distinct messages in the point-to-point communication mode. Alternatively, the queue limit could be set to 1 by concatenating all M messages into one message and using the broadcast mode of transmission. These options have their own merit and demerit and the choice of a specific option is a design issue.

The above observations are generic in nature and are applicable to other distributed digital control and communication systems (DDCCS) including those for spacecraft, power and chemical plants, and autonomous manufacturing proceses. Although the process dynamics in different applications may vary widely, the concept of dimensionless offered traffic and the resulting data latency relative to the average interarrival time, i.e., the sampling period for a periodic traffic is similar in all cases.

5 Summary and Conclusions

Performance of distributed digital flight control system (DDFCS) with SAE linear token bus (a distributed controlled access protocol) and MIL-STD-1553B (a centralized controlled access protocol) has been analyzed in view of the requirements for avionic applications. Performance evaluation was carried out using a combined discrete-event and continuous-time simulation approach. The simulation results were generated to demonstrate how the transport delays incurred in medium access control (MAC) protocols can degrade the dynamic performance of an aircraft.

The following conclusions regarding the DDFCS network design can be derived from the results of this research.

- For all protocols the critical value of offered traffic is important in view of loss of messages due to queue saturation as well as for the data latency especially if the queue limit is larger than 1. The network should be designed such that the offered traffic does not exceed the critical value. This implies that any combination of network design parameters (namely, the number of terminals on the medium, message generation rate, message length, medium bandwidth and sample time) should allow for a safe margin between the offered traffic and its critical value.
- The overshoot and settling time of transients for SAE token ring and linear token bus are distinctly superior to those for MIL-STD-1553B under identical network traffic because MIL-STD-1553B suffers from larger data latency due to larger message overhead and idle time. This also entails a relatively smaller critical offered traffic for MIL-STD-1553B resulting in a larger number of lost messages whenever offered traffic exceeds its critical value. Thus the DDFCS, in general, should have superior dynamic performance and stability if SAE linear token bus (or SAE token ring) is used instead of MIL-STD-1553B. However, this conclusion is made only on the basis of data latency where failure modes and reliability issues have not been addressed, and therefore should not be taken as the final conclusion.

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APPENDIX A

Transfer Functions of the Plant and Controller

The plant under consideration representing the actuator and rigid body dynamics of an advanced aircraft and modelled as follows.

$$\dot{\delta}_e = -\delta_e/\tau_e + \delta_a; \}\text{Actuator Dynamics}$$

$$\left.\begin{aligned} \dot{W} &= -Z_w W + U_0 q + Z_{de}\delta_e; \\ \dot{q} &= M_w W + M_q q + M_{de}\delta_e + \\ &\quad M_{\dot{w}}\dot{W} \end{aligned}\right\} \begin{array}{l}\text{Dynamics of Longitudinal} \\ \text{Motions of the Airframe}\end{array}$$

where

δ_a = Elevator command, i.e., input to the actuator (radian)
δ_e = Elevator deflection, i.e., actuator output (radian)
W = Normal longitudinal velocity (meter/s)
q = Pitch rate (radian/s)
τ_e = Actuator time constant (0.050 s)
U_0 = Velocity of sound in air (306.4 meters/s)

and the longitudinal dimensional stability derivatives [12] were chosen as

$M_{de} = -40.465$ radian/s
$M_q = -\ \ 2.684$ radian/s
$M_w = -0.04688$ radian/(meter.s)
$M_{\dot{w}} = -0.00377$ radian/meter
$Z_{de} = -61.655$ meter/s
$Z_w = -\ \ 3.1330$ radian/s

The plant output variables feeding the controller are

Pitch rate q,
Angle of attack $\alpha = W/U_0$, and
Body acceleration $A_N = -(\dot{W} - U_0 q + l\dot{q})$
where l = the distance between the center of gravity of the airframe and the accelerometer (3.74 meters).

From the above equation the transfer matrix $G_p(s)$ relating the plant outputs to the plant (and actuator) input can be computed.

The s-domain version of the controller transfer matrix (which was transformed into z-domain before using it in the simulation program) is presented below.

$$\delta_a(s) = \begin{bmatrix} \dfrac{0.437(s+5)^2}{(s+15)(s+1)} & \dfrac{16.386(s+5)^2}{s(s+15)^2} & \dfrac{2.979}{(s+10)} & \dfrac{-1.1(s+5)^2}{s(s+15)} \end{bmatrix} \begin{bmatrix} q(s) \\ A_N(s) \\ \alpha(s) \\ R(s) \end{bmatrix}$$

where R is the reference signal for body acceleration and is an input to the control system.

The eigenvalues (s^{-1}) of the 8th order closed loop system matrix (with a coninuous-time controller) are listed below

-0.593
-2.347
$-5.539 + j6.900$
$-5.539 - j6.900$
-12.001
$-13.669 + j10.133$
$-13.669 - j10.133$
-14.611

APPENDIX B

Simulation Model for Performance Evaluation on the DDFCS

Avionic network simulation serves several purposes including performance evaluation of flight control systems and investigation of potential failure modes and operational malfunctions. Since individual simulation languages may have their own specific structural constraints, selection of an appropriate simulation language is crucial for the development of a simulation program.

Commonly used discrete-event simulation languages are GPSS/H [13], SIMSCRIPT II.5 [14], SIMULA [15], SLAM [16], and SIMAN [17]. For the DDFCS network simulation the afore-said languages were evaluated in terms of (1) combined discrete-event and continuous-time simulation capabilities, (2) programming flexibility, (3) program portability, (4) modularity and structured programming, (5) verification and run-time debugging, and (6) built-in data analysis and real-time event scheduling capabilities. In view of the above requirements, SIMAN was selected as the language for DDFCS simulation. The rationale for selection of SIMAN and its comparison with other simulation languages are provided in [18].

The simulation program for the closed loop distributed digital flight control system (DDFCS) consists of two independent and interacting models: (1) a discrete-event model of the network, and (2) a continuous-time model of aircraft dynamics and discrete-time model of the flight controller. The program structure is modular, i.e., and one of the protocol models (e.g. MIL-STD-1553B or SAE token ring or SAE token bus) can be inserted in the simulation program while operating on the same control system model and vice versa.

The network model consists of two independent but interacting submodels: message generation submodel and 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 (Poisson arrival for example). Similarly, the message lengths can be either constants or randomly distributed (exponential for example). As a message arrives at the transmitter buffer of a terminal, the message characteristics are described by a number of attributes which are defined below.

- Time of generation—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 (where 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.

APPENDIX C

Critical Offered Traffic for Individual MAC Protocols

Calculations for critical offered traffic (in Definition 8) are supported by Definitions and Remarks in Section 3 as well as by the data in Table I. Following the scenario described in Section 4, the sampling period is 10 ms and each of the plant and controller terminals has 64 bit long data, i.e., 4 data words for SAE linear token bus, SAE token ring, and MIL-STD-1553B protocols [9, 10, 11]. The remaining 29 terminals has m data words which are varied to obtain selected values of offered traffic G. The calculations for the critical offered traffic G_{cr} for the three protocols are given below.

SAE Linear Token Bus. From Table 1, $R=50$ Mbits/s, $\sigma=0.5$ μs, $w_f=16$ bits, and $L=72$ bits. The unknown integer m is evaluated by setting the cycle time τ equal to the sampling period T under critical traffic conditions. $2(84+64) + 29(16m+84) = [10\times10^{-3} - 31(0.5\times10^{-6})]\times(50\times10^{6})$ yields integer $m=1070$. Using this value of m, the critical offered traffic is computed as $G_{cr} = (2\times64 + 1070\times16\times29)/[50\times10^{6}\times(10\times10^{-3}] \approx 0.993$.

SAE Token Ring. From Table 1, $R=40$ Mbits/s, $\sigma=1$ μs, $w_f=16$ bits, and $L=132$ bits. Using the above procedure, under critical traffic conditions, the integer m is computed to be 850. Thus, $G_{cr} \approx 0.986$.

MIL-STD-1553B (*Command/Response Mode*). From Table 1, $R=1$ Mbits/s, $w_f=20$ bits, and the overhead and idle time yields a time delay of 108 μs for *RT* to *RT* transfer and 56 μs for *BC* to *RT* and *RT* to *BC* transfers [11]. In one cycle there are 29 *RT* to *RT* transfers, one *BC* to *RT* transfer, and one *RT* to *BC* transfer. Since $w_f=20$, each of the plant controller terminals has 4 data words having a formatted length of 80 bits. The data word in each of the remaining 29 terminals will have formatted length of 20m bits. Under critical traffic conditions, $2(80 + 56) + 29(20m + 108) = 10000$ yields integer $m=11$. Thus $G_{cr} = (2\times64) + 29\times11\times16)/10000 \approx 0.523$.