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A Fiber-Optic Network Protocol for Computer Integrated Manufacturing*

This paper presents the architecture and performance analysis of a fiber-optic-based network protocol for computer integrated manufacturing (CIM). Its adaptation as the common medium access control (MAC) layer protocol in the fiber-optic-based version of the Manufacturing Automation Protocol (MAP) and Technical and Office Protocols (TOP) will make their specifications identical up to the presentation layer; only the application layer which is user specific could be different.

1 Introduction

The goal of Computer Integrated Manufacturing (CIM) is to put together the diverse areas of engineering, design and production processes, material inventory, sales and purchasing, and accounting and administration into a single interactive closed loop control system [1]. Essential to this distributed total manufacturing system is the integrated communications network over which the information leading to process interactions, and plant management and control will flow. Such a network must be capable of handling heterogeneous real-time (RT), e.g., data packets for inter-machine communications at the factory floor, and non-real-time (NRT), e.g., CAD drawings, design specifications and administrative information, data traffic. In general, RT data have short packet lengths and are frequently transmitted (for example, a robot trajectory control system may require transmission of a few words long packets every 20 milliseconds) whereas NRT data have long packets and are transmitted rather infrequently. While data latency is a critical factor for RT data, data integrity is essential for NRT data [2]. The high data rate, possibly on the order of 1 Gbps, and wavelength multiplexing capability of fiber optic media would allow handling of heterogeneous (e.g., RT and NRT data, voice, video, and facsimile) traffic in CIM networks within the same transmission medium. Currently the medium access control (MAC) layers in MAP [3] and TOP [4] which have been largely accepted as standards for CIM networking are not designed for interfacing with fiber optic media. Furthermore since information flow in the CIM environment is not restricted within individual regions such as office and factory zones, TOP and MAP and the individual subnets within the network must communicate with each other via bridges and routers which are potential sources of delay and congestion due to the inter-net traffic.

The above discussions as well as the recommendations of a recent workshop on computer networking [1] evince the need for developing appropriate protocol(s) for handling both of office

and factory communication traffic over fiber optic transmission media. The key issue is whether the fiber-optic-based MAC protocols should simply replace the existing MAC layer protocols in TOP and MAP or a new protocol should be developed for handling the heterogeneous traffic of office and factory communications within a single fiber-optic medium. The latter option will eliminate the need for bridges and routers between local zones, which are sources of potential delay and congestion. Furthermore since the architectures of MAP and TOP are similar except for the MAC and application layers, using a common MAC layer will make MAP and TOP specifications identical up to the presentation layer. Only the application layer which is user-specific could be different.

This paper reports the development of a novel fiber-optic-based protocol for integrated factory and office communications. The paper is organized in six sections including the introduction. The current status of networking in CIM is briefly discussed in Section 2, and the architecture of the proposed protocol for CIM networks is presented in Section 3. A discrete-event simulation model of the protocol is described in Section 4, and the simulation results for a specific scenario of CIM traffic are discussed in Section 5. Finally the paper is concluded in Section 6.

2 Current Status of Networking in CIM

A typical network architecture commonly used in manufacturing systems to serve rigid work cells is shown in Fig. 1. The intra-cell devices are served by carrier band networks and the inter-cell communication takes place via the broadband backbone network. As seen in Fig. 1, the data communication across two networks is supported by bridges and routers which could be sources of additional delay and congestion in the inter-network path. Furthermore the rigid cell architecture of a manufacturing facility limits the flexibility of the system under the dynamic environment of batch manufacturing processes. A high degree of flexibility and modularity in manufacturing automation can be achieved by partitioning the factory floor facilities into virtual cells. The concept of a network architecture for an integrated office and factory communication system via a single high-speed medium is illustrated in Fig. 2. This architecture would potentially realize the concept

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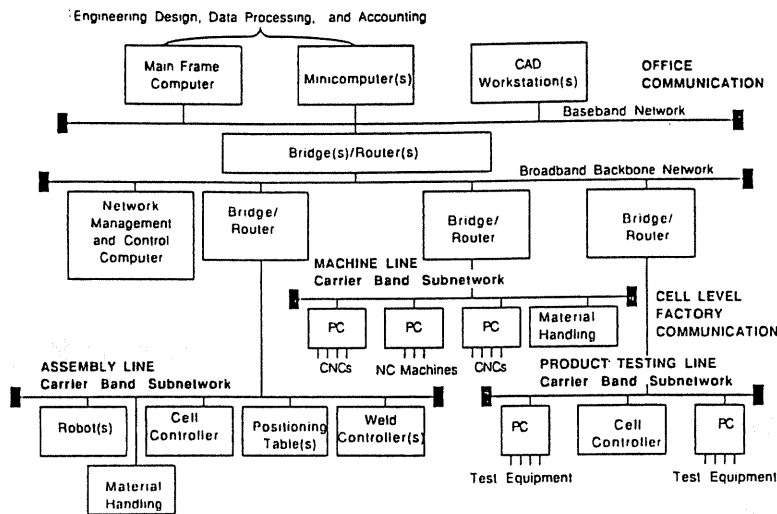


Fig. 1 Conventional networking for CIM

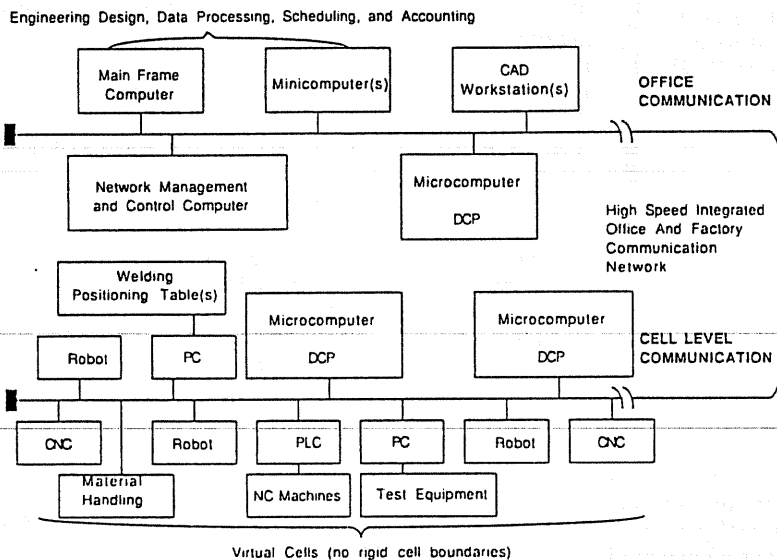


Fig. 2 Integrated networking concept for CIM

of virtual cells to facilitate dynamic reallocation of resources in an autonomous manufacturing environment. The advantages and disadvantages of the proposed networking concept in Fig. 2 are discussed in [2].

The delay requirements of heterogeneous traffic in CIM networks have not been seriously considered in the design of the medium access control (MAC) protocols. In a manufacturing environment, network traffic can be broadly classified into two categories: real-time (RT) and non-real-time (NRT). The RT messages have an upper bound on the acceptable data latency which is largely dependent on the type of application (for example, delays on the order of 20 ms can often be allowed for coordinated control and trajectory planning for a pair of robots). Occasional loss of the above messages is tolerable but additional delays due to retransmission of the lost packets may not be acceptable. Therefore, RT data transmission does not require the acknowledgment scheme [2]. On the other hand, NRT messages (viz., large program files, CAD files and drawings) are usually long, non-periodic, and less frequent. A stringent upper bound on delay does not exist for these NRT messages but the integrity of the data cannot be compromised. An acknowledgment scheme is required for NRT data transmission to ensure error free delivery. Whereas data latency is a critical factor for RT messages, reliable delivery is essential for NRT messages. RT signals should be allowed to interrupt the NRT data transmission. The preemption will increase the

data latency of NRT messages but will significantly increase the probability of timely delivery of RT messages. Accurate delivery of all NRT messages is assured by the acknowledgment and retransmission scheme which could possibly be resident at the transport layer in the protocol suite.

Fiber optics offer a variety of network topologies that include star, ring, and unidirectional bus. Since manufacturing processes are distributed and must highly reliable to ensure continuity of production, star topology may not be appropriate for CIM. On the other hand, ring topologies like Fiber Digital Data Interface (FDDI) use explicit token passing where store-and-forward mechanism at each station induces a significant amount of delay especially if the network consists of a large number of stations. Although FDDI provides different levels of priority, it does not guarantee delivery of a message before that of a lower priority message at another station. Furthermore, explicit token passing in FDDI may cause additional delays due to re-initialization in the event of token loss. Baseband Technical and Office Protocols (TOP) [3] and broadband Manufacturing Automation Protocol (MAP) [2], which currently use coaxial cables as network media, have been largely accepted as standards for CIM networking. TOP is primarily designed for office automation and MAP for factory automation. The bus topology is used in both TOP and MAP. TOP utilizes the IEEE 802.3 CSMA/CD protocol at the MAC layer. Although CSMA/CD operates efficiently at light traffic,

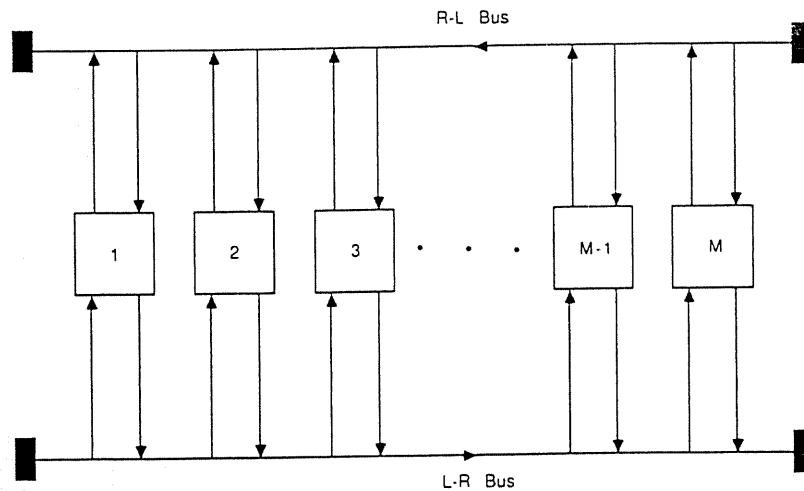


Fig. 3 Topology of the unidirectional dual bus system (serving M stations)

the performance in terms of throughput and data latency significantly deteriorates as the ratio of propagation delay to packet transmission time increases [5]. With fiber optic media in the CIM environment, this problem is likely to be very severe due to large separation distances between the end users and the high transmission rate. This would result in frequent collisions followed by significant degradation of network performance (e.g., delay and throughput). Although there are instances of implementing CSMA/CD using fiber optics (Fibernet II [6] with active star topology, for example), the CSMA/CD protocol may not prove to be compatible with fiber optic media in the CIM environment. The MAC layer protocol in MAP is the IEEE 802.4 token passing bus protocol where the access mechanism uses explicit token passing [7]. Since implicit token passing yields a better performance (e.g., smaller delays and larger throughput) than explicit token passing at a high transmission data rate and for a large number of terminals, IEEE 802.4 token passing may not be a good choice for fiber optic media in the CIM environment. The above limitations of the existing versions of TOP and MAP can be alleviated by a hybrid MAC protocol operating on a fiber optic medium. A number of hybrid MAC protocols have been developed specifically for fiber optic media to utilize their high bandwidth capacity. These protocols are principally based on the Demand Assignment Multiple Access (DAMA) scheme using the concept of implicit token passing [7]. On the basis of the results reported in [8], Buzznet appears to be generally superior to other fiber-optic-based hybrid protocols. Buzznet operates in the random access mode using CSMA/CD under low traffic conditions and switches over to implicit token passing in the controlled access mode if a collision occurs. However, CSMA/CD is prone to frequent collisions under a large propagation delay and high data transmission rate for fiber optic media. In this case, the protocol performance would suffer due to repeated switching between the random access and controlled access modes. In addition, since heterogeneous data traffic in the CIM environment consists of RT and NRT data traffic [2] and Buzznet does not have a built-in priority scheme, RT messages will encounter large delays. This justifies the need for development of a new fiber-optic-based protocol that will overcome the deficiencies associated with Buzznet and other protocols.

3 Description of the Proposed Protocol

The essential features of the proposed protocol are described in this section; the details are reported in [9, 10]. Figure 3 illustrates the unidirectional dual bus topology (with active or passive taps) which has been adopted in this protocol and is

compatible with fiber optic media. An important property of the above topology is that any receiving station can identify relative location of the transmitting station. This feature can be exploited for autonomous isolation of a faulty station that does not adhere to the access schedule. On this basis, it is possible to design a fault-accommodating architecture of the CIM network that will be tolerant of several unattended failures with self-repair capability.

The protocol is formulated using the concept of Buzznet's controlled access mode. The following features, not addressed in the Buzznet, have been incorporated in the proposed protocol:

- Accommodation of heterogeneous (i.e., RT and NRT) traffic of the CIM environment within a single network medium.
- Built-in prioritization of RT messages.

At a given instant, a station is allowed to operate in exactly one of the two modes: real-time (RT) access mode and non-real-time (NRT) access mode. Each mode is initiated by a pattern of bit sequence, known as the jamming signal, and terminated by another such pattern, known as the unjamming signal. The jamming signals for the RT and NRT modes are denoted as RT-JAM and NRT-JAM, respectively. Similarly, the respective unjamming signals are denoted as RT-UJAM and NRT-UJAM. An RT message may preempt an NRT message by an RT-JAM which also serves as the preamble for receiver synchronization. Each station is provided with two timers to control the bus operations under both RT and NRT modes:

- *Bus Activity Timer (BAT)* is started if both buses are sensed idle. If any activity is detected within the round-trip propagation delay between two farthest stations, then the timer is reset; else it expires.
- *Preemption Timer (PT)* is started upon arrival of an RT message. If the timer is not reset, it expires after a period of αT where T is the upper bound of the data latency for an RT message and $\alpha \in (0,1)$ is an adjustable parameter. α can be updated on the basis of network performance by the network management function which is possibly located at an upper layer.

The operations of the proposed protocol at a given station, as illustrated in the timing diagram in Fig. 4, are classified into two message cycles, namely, RT and NRT, and two phases, namely, *contention* and *controlled access*. The contention phase is the process of scheduling both RT and NRT message transmissions such that a station in the contention phase with RT message(s) can take control of the bus by transmitting an RT-

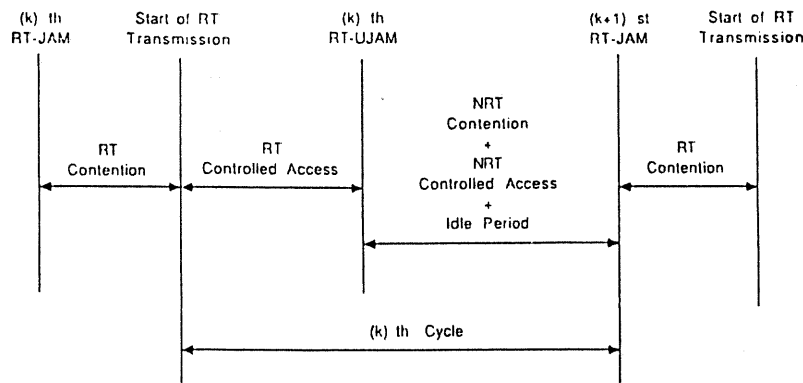


Fig. 4 Timing diagram of RT and NRT modes

JAM signal while the remaining NRT frames have to wait for another opportunity. The controlled access phase follows the contention phase and is the process of transmitting both RT and NRT message(s). The RT cycle is the interval between the end of the RT contention phase and the instant of sensing RT unjamming or BAT expiration. The NRT cycle is the interval between the first-time end of the NRT contention phase (which occurs immediately after sensing of NRT unjamming or BAT expiration) and the instant of subsequently sensing NRT unjamming pattern or BAT expiration.

Remark 1: The role of the preemption timer α is, to some extent, analogous to that of the target token rotation timer (TTRT) in the FDDI protocol. However, unlike TTRT which always affects the network performance, α influences the network performance only when it is necessary, e.g., when the network system is backlogged with RT message(s) under medium or high traffic conditions. This feature is particularly important if the network is required to handle RT messages with extremely short delay bounds, e.g., multi-robot control systems in inter-cell operations.

Remark 2: Since an NRT cycle may be preempted by RT cycle(s), the beginning of the NRT cycle may be followed by NRT contention modes as shown in Fig. 4.

The access mechanism of this protocol is collision free for both RT and NRT modes. Upon arrival of an RT message a station starts its PT. The station enters the contention phase if the PT or BAT is expired, or if it detects RT-JAM. In the contention phase, stations with backlog messages transmit the RT-JAM signal on both buses for a period of twice the round-trip propagation delay. If no RT-JAM is detected from any upstream station on L-R (or R-L) bus, then the station identifies itself to be in the leftmost (or rightmost) backlogged station. Following the transmission of RT-JAM signals on both buses, the backlogged stations engaged in the contention process transmit RT-JAM signals again only on the L-R bus deferring to any upstream RT-JAM such that the leftmost backlogged station starts transmitting its waiting RT messages on both buses. In this way, the stations with backlogged RT message(s) establish a logical ring for the implicit token passing mechanism. The last station in this logical ring will know that there are no more contending stations as it does not detect any RT-JAM signal during the contention phase of this cycle.

Following the contention phase, the stations enter the controlled access phase in which messages are transmitted according to the attempt and defer access mechanism. Upon successfully transmitting an RT message, the station awaits for detection of RT-UJAM. The last station in the logical ring, upon transmitting its message, issues RT-UJAM to indicate that the RT cycle is terminated. The preemption scheme within the RT mode operates as follows. If a station is transmitting an NRT message and an RT message arrives at that or any other station, then the ongoing transmission of the NRT mes-

sage is allowed to be completed. Then the station(s) with RT message(s) take control of the bus while the remaining NRT frames have to wait for another opportunity. The interruption of NRT messages does not jeopardize their integrity because of the built-in acknowledgment scheme and retransmission capability. The operations in the NRT mode are similar to those in the RT mode except that a backlogged station enters the contention phase upon detecting both buses to be idle or NRT-JAM. If the station detects RT-JAM, it immediately aborts all operations and awaits for RT-UJAM or BAT expiration.

4 Discrete-Event Simulation of the Proposed Protocol

The goal of discrete-event simulation is to evaluate the protocol performance under diverse operating conditions of CIM networks. The simulation model is formulated on the basis of a timed Petri net model [11] which represents sequences of concurrent and parallel processes in protocol operations. The timed Petri-net model consists of three interesting submodels for: (i) real-time (RT) access; (ii) non-real-time (NRT) access; and (iii) channel communications. The RT and NRT access submodels represent the protocol operations in RT and NRT modes, respectively, as described in Section 3. The channel communication submodel comprises of transactions and propagation delays between adjacent stations. A detailed description of the timed Petri net model is given in [10].

The simulation model directly follows and is structurally similar to the timed Petri net model. It is made up of three similar submodels representing the real-time (RT) mode, non-real-time (NRT) mode, and communication channel activities. Each of the RT and NRT submodels is further divided into two functional subsystems: message generation and protocol operation. The message generation subsystems in both RT and NRT submodels schedule arrival of messages at each station in the network whereas the protocol operation subsystem essentially defines the access mechanism of the protocol in the particular mode. Simulation is initiated by scheduling the arrival of messages, and the message arrival rates and lengths can be deterministic or random. The arrival rates of RT messages (for example, those messages that are generated by production processes in the factory environment) are likely to be deterministic and so are the message lengths. In contrast, the arrival rates and lengths of NRT messages (for example, messages that are generated by design and administrative processes in the office environment) are likely to be randomly distributed. In both cases the arrival of one message automatically reschedules the event for the next arrival. The protocol operation subsystems in both RT and NRT submodels define the access mechanism, and are initiated by the respective message generation subsystems upon arrival of a message into the network. The message generation and protocol operation subsystems are thus linked together, and this is accomplished via call

statements from each protocol operation subsystem to other appropriate subsystem(s).

The discrete-event simulation model is developed using a commercially available program [12] which offers ease of program development, debugging and verification, software portability, structured data input, flexible output formatting, automatic statistics collection, and event sequencing. The simulation program contains two major files: experiment and model. The protocol parameters are defined in the experiment file. The model file can be structured as block oriented or event-driven or a combination of both. The event-driven functions are more flexible as it allows the model file to be augmented by user-written FORTRAN subroutines. Program-specific primitive functions can be addressed directly via CALL statements.

5 Simulation Results Under a Specific Scenario

Within a CIM networking environment, the proposed protocol provides flexibility for coordinated control of inter-cell equipment. The intent is to evaluate performance of the protocol under the heterogeneous traffic of integrated office and factory communications where the allowable bounds for data latency of RT messages are determined by the functional characteristics of the controlled processes. A few examples where network-induced delays could be critical for dynamic performance and stability of real-time processes are given below.

In an intelligent welding system [13, 14] where a positioning table and a robot may not be hardwired to the same computer, the table position coordinates could be relayed to the robot controller via the network. The robot controller, in turn, may transmit back signals for a more convenient table position. This requires timely arrivals of the data at both machines.

Two robots are coordinated in a master-slave configuration while handling a bulky workpiece together. If these two robots do not belong to the same supervisory computer, they will communicate via the network so that the slave robot follows a prescribed trajectory. The timeliness of the transmitted data is essential because a delay could damage the workpiece or the robot's wrists and arms.

In a machine tool transfer line, several machines are assisted by robots for loading, unloading and handling of materials and parts. The timeliness of interrupt signals arriving at individual machines is critical for successful operations.

Accurate delivery of NRT messages, such as CAD drawings, material inventory and payroll files, is essential although they do not have stringent data latency requirements. The integrity of the message delivery is achieved by acknowledgment schemes that are usually implemented at higher layers in the protocol suite. The network traffic, resulting from typical office and factory operations, is not likely to conform to the assumptions of independent Poisson processes that are usually made in formulating the analytical model [10]. Therefore, performance of the protocol is evaluated by simulation where two different cases of settings $\alpha = 0.0$ and $\alpha = 0.5$ of the preemption timer, defined in Section 3, have been considered in the following traffic scenario.

A manufacturing scenario has been made up of five virtual cells where each cell is composed of a number of RT and NRT processes. The RT messages from machine tools and devices are classified into two categories: (i) periodically generated sensor and control signals; and (ii) interrupt signals which may arrive in bursts and their inter-arrival time is assumed to have an exponential distribution. On the average, each cell consists of 20 machines. Each of these machines periodically generates 10 different sensor and control signals every 100 ms and randomly generate interrupt signals with a mean inter-arrival time of 10 ms. The sampling instants of the periodic signals are

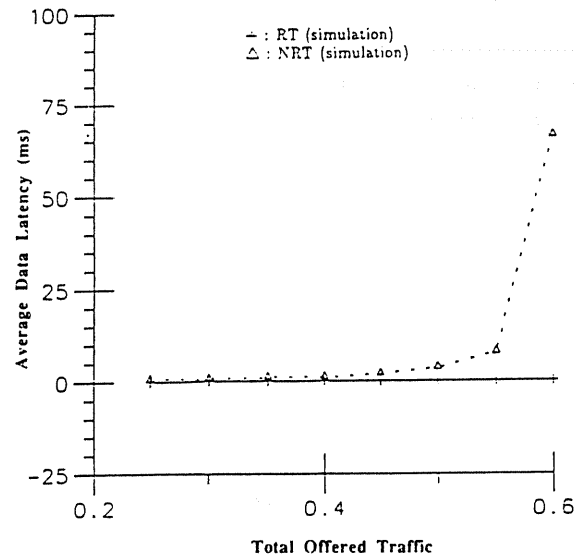


Fig. 5 Simulation results for a specific scenario ($\alpha = 0.0$)

uniformly distributed 10 ms and 90 ms. On the average, one periodic message and one random RT message are generated by each machine at every 10 ms. The RT message lengths are usually very short and individual messages may vary in length in an actual manufacturing environment. However, for simplicity, the RT message length and data latency bound are taken to be 1000 bits and 10 ms, respectively, and the offered traffic ρ_{RT} for RT messages is maintained at 0.20 in this simulation example. The performance of the proposed protocol is evaluated by varying the NRT traffic while ρ_{RT} is held constant. NRT messages are usually much longer than RT messages, and widely vary in lengths. In this example, NRT message lengths are assumed to be uniformly distributed between 25000 and 75000 bits. The arrival process of NRT messages is normally bursty, and is assumed to be Poisson in the simulation example. The average arrival rate of NRT messages are adjusted as the total offered traffic, ρ_{tot} , is increased. The network parameters used in the simulation of the protocol under the above scenario are summarized below.

$\rho_{RT} = 0.20$ and ρ_{tot} is increased up to 0.6 by increasing NRT traffic; Number of RT stations = 5 and number of NRT stations = 5; Data transmission rate in the fiber optic medium = 100 Mbps; RT message transmission time (constant) = 0.01 ms; NRT message transmission time is uniformly distributed in (0.25, 0.75) ms.; Upper bound of RT message data latency = 10.0 ms; Length of the network bus = 2 km; One way propagation delay = 0.01 ms; Propagation delay between adjacent stations = 0.002 ms. Station response time = 0.000 ms. End of cycle unjamming pattern = 5 bits, i.e., 0.00005 ms.

Figures 4 and 5 illustrate how the expected values of data latencies, D_{RT} and D_{NRT} of RT and NRT messages, respectively, change as ρ_{tot} is increased for two cases of $\alpha = 0.0$ and $\alpha = 0.5$, respectively. Table 1 shows the cumulative relative frequency of the number of transmissions whose data latency does not exceed the specified bounds for RT and NRT messages under different values of ρ_{tot} in both cases. RT message arrival is a mixed periodic and exponentially distributed process whereas NRT message arrival is a Poisson process. Since dynamic performance and stability of RT processes depend on the timely arrival of scheduled messages, it is critical to maintain the data latency of RT messages within a specified bound at a very high level of confidence. However, although not essential, small data latency is desirable for NRT operations for reduction of the buffer size to store the waiting messages.

Table 1 Confidence level of message data latency

Case I: ($\alpha = 0.0$)

Real-time data latency bound = 0.69 ms.

Non-real-time data latency bound = 154.00 ms.

ρ_{tot}	Real-time	Non-real-time
0.25	0.9954	1.0
0.30	0.9898	1.0
0.35	0.9796	1.0
0.40	0.9762	1.0
0.45	0.9691	1.0
0.50	0.9633	1.0
0.55	0.9544	1.0
0.60	0.9503	0.9511

Case II: ($\alpha = 0.5$)

Real-time data latency bound = 3.50 ms.

Non-real-time data latency bound = 7.05 ms.

ρ_{tot}	Real-time	Non-real-time
0.25	1.0	1.0
0.30	1.0	1.0
0.35	1.0	1.0
0.40	1.0	1.0
0.45	0.9991	0.9990
0.50	0.9891	0.9940
0.55	0.9891	0.9876
0.60	0.9521	0.9517

Case I: (Preemption Timer Parameter $\alpha=0.0$). Figure 5 shows that D_{RT} is practically independent of ρ_{tot} whereas D_{NRT} gradually increases with ρ_{tot} and this increase becomes very sharp beyond $\rho_{tot}=0.55$. At $\alpha=0.0$, an arriving RT message immediately preempts the bus if the protocol is executing in the NRT mode and transmits the backlogged RT message (after allowing for completion of any ongoing NRT message transmission). This results in significant reduction of D_{RT} . The periodic preemption and the additional overhead due to contention of RT cycles restrict the protocol operation in the NRT mode, resulting in delayed transmission of NRT messages. Therefore, the expected value of D_{NRT} follows an approximately exponential profile as ρ_{tot} is increased. Similar results are expected from token passing bus and FDDI protocols under high traffic load conditions [15]. If there exist processes with very fast dynamics, i.e., short data latency bound on RT messages, NRT messages would be significantly delayed and the NRT throughput might be severely limited if the target token rotation timer (TTRT) of FDDI is set to a small value to satisfy the bound of D_{RT} .

Case II: (Preemption Timer Parameter $\alpha=0.5$). Figure 6 shows how D_{RT} and D_{NRT} change with increase in ρ_{tot} . Unlike Case I in Fig. 5, D_{RT} does not remain constant and D_{NRT} does not rise sharply. At low ρ_{tot} , the setting of $\alpha = 0.5$ does not significantly influence the RT message transmissions because the bus activity timer dominates over the preemption timer. As ρ_{tot} increases, the preemption timer parameter becomes more effective and D_{RT} tends to increase. With an increase in ρ_{tot} , the setting of $\alpha = 0.5$ reduces the effect of periodic preemption by RT messages and RT contention period overheads. Compared to Case I, a larger amount of bandwidth is available for NRT message transmissions, which results in decreased D_{NRT} . The Cases I and II, discussed above, indicate the effectiveness of the proposed protocol for timely delivery of RT messages and also of NRT messages if the medium bandwidth is used for RT transmissions. Case I with $\alpha=0.0$ is a con-

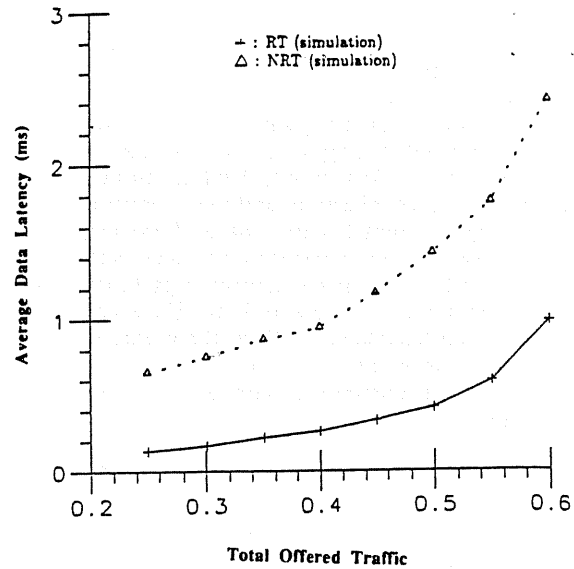


Fig. 6 Simulation results for a specific scenario ($\alpha=0.5$)

servative design for the given network traffic allocation. Therefore Case II with $\alpha=0.5$ was considered to illustrate the effectiveness of the redemption timer in the proposed protocol for a trade-off between a small increase in D_{RT} and a large decrease in D_{NRT} . An optimal value of α depends on both the performance index and the statistical characteristics of RT and NRT traffic. The role of the preemption timer is, to some extent, analogous to that of the target token rotation timer (TTRT) in the FDDI protocol. However, unlike TTRT which always affects the network performance, α influences the network performance only when it is necessary, e.g., when the network system is backlogged with RT message(s) under medium or high traffic conditions. This aspect is particularly important if the network is required to handle RT messages with extremely short data latency bounds (for example, multi-robot control systems in inter-cell operations).

6 Summary and Conclusions

A fiber-optic-based protocol has been proposed for computer integrated manufacturing (CIM) networks. The architecture of the protocol is suitable for heterogeneous traffic in an office and factory environment. A discrete-event simulation model of the protocol has been developed to evaluate performance, i.e., delay and throughput, of both real-time and non-real-time messages under different traffic scenarios. The protocol performance has been tested by simulation experiments under a specific scenario that represents data communications in a CIM network environment. The simulation experiments demonstrate efficacy of the proposed protocol for prioritization of the real-time messages for a better utilization of the transmission medium bandwidth such that the unused bandwidth can be made available to the non-real-time traffic. The results from the two cases (having the preemption timer parameter α set to 0.0 and 0.5) reveal that, in order to take advantage of real-time message handling capability of the proposed protocol at high total offered traffic, an optimal value of α should be selected. Future research is recommended for development of a methodology for optimization of α under specified network operating conditions. Another possible area of research is development of analytical tools for tuning network parameters (such as the preemption timer parameter α and frame lengths for RT and NRT messages) for efficient performance of the network. Techniques, such as perturbation analysis [16, 17], stochastic optimization [18], and learning

automata [19], may be used for performance management of the network as proposed by Lee and Ray [20].

References

- 1 Ray, A., and Phoha, S., 1989, "Research Directions in Networking for Manufacturing Systems," *ASME JOURNAL OF ENGINEERING FOR INDUSTRY*, Vol. 111, No. 2, May, pp. 109-115.
- 2 Ray, A., 1988, "Networking for Computer-Integrated Manufacturing," *IEEE Network*, Vol. 2, No. 3, May, pp. 40-47.
- 3 Manufacturing Automation Protocol (MAP) 3.0 Implementation Release, Available through MAP/TOP Users Group, One SME Drive, P.O. Box 930, Dearborn, MI 48121.
- 4 Technical and Office Protocols (TOP) 3.0 Implementation Release, Available through MAP/TOP Users Group, One SME Drive, P.O. Box 930, Dearborn, MI 48121.
- 5 Stallings, W., *Data and Computer Communications*, Macmillan Publishing Company, New York, 1985.
- 6 Moustakas, S., 1987, "The Standardization of IEEE 802.3 Compatible Fiber Optic CSMA/CD Local Area Networks," *IEEE Communications Magazine*, Vol. 27, No. 2, Feb. 1987, pp. 22-29.
- 7 Fine, M., and Tobagi, F. A., 1984, "Demand Assignment Multiple Access Schemes in Broadcast Bus Local Area Networks," *IEEE Trans. Computers*, Vol. C-33, No. 12, December, pp. 1130-1159.
- 8 Gerla, M., Wang, G., and Rodrigues, P., 1987, "Buzz-Net: A Hybrid Token/Random Access LAN," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 6, July, pp. 977-988.
- 9 Ayyagari, A., and Ray, A., 1990, "A Fiber-optic-based Protocol for Manufacturing System Networks: Part I—Conceptual Development and Architecture," ASME Paper No. 90-WA/DSC-3, presented at the ASME Winter Annual Meeting, Dallas, TX, November 1990.
- 10 Ayyagari, A., 1989, "A Fiber-optic-based Protocol for Manufacturing System Networks," Ph.D. Dissertation, The Pennsylvania State University, August.
- 11 Peterson, J. L., 1981, *Petri Net Theory and The Modeling of Systems*, Prentice Hall, Englewood Cliffs, NJ, 1981.
- 12 Pegden, C. D., 1986, *Introduction to SIMAN*, Systems Modeling Corporation, State College, PA.
- 13 Thompson, D. R., Ray, A., and Kumara, S., 1988, "A Hierarchically Structured Knowledge Based System for Welding Automation and Control," *ASME JOURNAL OF ENGINEERING FOR INDUSTRY*, February, pp. 71-76.
- 14 Nayak, N., Ray, A., and Vavreck, A. N., 1987, "Adaptive Real-Time Intelligent Seam Tracking Systems," *Journal of Manufacturing Systems*, Vol. 6, No. 3, September, pp. 241-245.
- 15 Dykeman, D., and Bux, W., 1988, "Analysis and Tuning of the FDDI Media Access Control Protocol," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-6, No. 6, July, pp. 997-1010.
- 16 Ho, Y. C., 1987, "Performance Evaluation and Perturbation Analysis of Discrete-Event Dynamic Systems," *IEEE Trans. Automatic Control*, Vol. AC-32, No. 7, July, pp. 563-572.
- 17 Ho, Y. C., and Li, S., 1988, "Extensions of Infinitesimal Perturbation Analysis," *IEEE Trans. Automatic Control*, Vol. AC-33, No. 5, May, pp. 427-438.
- 18 Rubinstein, R. Y., 1986, *Monte Carlo Optimization, Simulation, and Sensitivity of Queueing Networks*, John Wiley.
- 19 Narendra, K. S., and Thatachar, M. A. S., 1989, *Learning Automata*, Prentice Hall.
- 20 Lee, S., and Ray, A., 1991, "Performance Management of Multi-Access Communication Networks for Large Scale Integrated Systems," *American Control Conference*, Boston, MA, June, pp. 475-480.