

A Fiber-Optic-Based Protocol for Manufacturing System Networks: Part I—Conceptual Development and Architecture¹

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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 (e.g., data packets for inter-machine communications at the factory floor) and non-real-time (e.g., Computer Aided Design (CAD) drawings, design specifications, and administrative information) traffic. This sequence of papers in two parts presents the development and analysis of a novel fiber-optic-based medium access control (MAC) protocol for integrated factory and office communications. Its adaptation as the common MAC layer protocol in the fiber-optic-based version of Manufacturing Automation Protocol (MAP) [2] and Technical and Office Protocols (TOP) [3], will make their specifications identical up to the presentation layer; only the application layer which is user-specific could be different. This first part provides the necessary background for the reported work and details of the protocol which is represented by a finite-state-machine model. Part II [4] presents the performance analysis of the protocol using a statistical model, and a comparison of the simulation and analytical results.

1 Introduction

Advances in Computer Aided Design (CAD), Computer Aided Engineering (CAE), and Computer Aided Manufacturing (CAM) have created islands of automation that do not often very effectively contribute to the overall productivity gain [1]. One major reason is that the individual subsystems do not always have an access to the common information base. 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. The architecture and performance of the network that interconnects these diverse functions are of paramount importance to the efficient and reliable operation of integrated manufacturing processes.

Such a network must be capable of handling heterogeneous real-time (e.g., data packets for inter-machine communications at the factory floor) and non-real-time (e.g., CAD drawings, design specifications and administrative information) traffic. (Voice and video information may also be integrated with data traffic in the future.) In general, real-time 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 non-real-time data have long packets and are transmitted rather infrequently. While data latency is a critical factor for real-time data, data integrity is essential for non-real-time data [5].

The unique features of optical fibers [6, 7] as network media are high data transmission, low attenuation, immunity to electromagnetic interference (EMI), electrical isolation, and resistance to fire and electrical hazards in contrast to those of coaxial cables. These characteristics make optical fibers particularly suitable as transmission media for CIM networks that must handle a potentially very large volume of heterogeneous traffic and operate in the hazardous environments of factory floor [1]. However, the physical characteristics of electro-optic components associated with fibers impose certain limitations on the network architectures at the medium access control (MAC) layer. Some of these restrictions are fundamental to

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the optical media while the others, such as excessive loss of energy at the connectors, are expected to be diminished with advancement in technology.

The high data rate, possible on the order of 1 Gbps, and wavelength multiplexing capability of fiber optic media would allow handling of heterogeneous (e.g., real-time and non-real-time data, voice, video, and facsimile) traffic in CIM networks within the same transmission medium. Currently the MAC layers in MAP [2] and TOP [3] 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 MAP must communicate with each other via bridges or routers. This phenomenon is illustrated in Fig. 1. Since advances in automation such as distributed artificial intelligence in manufacturing [8] are expected to generate significantly increased interactions between different subnets, the bridges and routers are potential sources of delay and congestion due to this growing 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 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 sequence of papers reports the development, analysis and simulation of a novel fiber-optic-based protocol for integrated factory and office communications. This paper is the first of two parts. It provides the necessary background for the reported work and details of the protocol that has been developed for manufacturing system networks. In particular, the following topics are discussed: (1) a survey of medium access control (MAC) protocols; (2) networking system requirements in view of CIM applications; and (3) details of the protocol operations supported by a finite-state-machine representation. Part II [4] presents the performance analysis of the protocol using a statistical model. The simulation results are then compared with the results of the analytical model. This comparison is followed by simulation results under a specific operational scenario for which the analytical model may not be valid. The sequence of papers is concluded in the

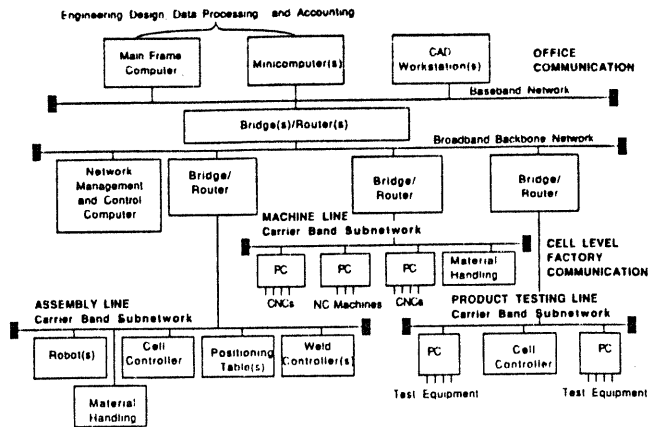


Fig. 1 Conventional networking for CIM

second part with recommendations for future work in the evolving field of networking for CIM.

This first part is organized in five sections including the introduction. Section 2 presents the taxonomy of medium access control protocols for different topologies of computer networks. Section 3 discusses the current status of networking in CIM and its future evolution using the fiber optic technology. The proposed protocol, based on fiber optics, is described in Section 4. Summary and conclusions for this part are given in Section 5.

2 Taxonomy of Medium Access Control Protocols

The broadcast communication in multi-access networks is achieved by using scheduling techniques, known as medium access control (MAC) protocols, which arbitrate between the competing subscribers for the privilege to use the network [9]. This section provides a brief overview of the major MAC protocols that are applicable to networks with optical fiber media; a comparison of various MAC protocols are given in detail by Fine and Tobagi [11]. The structure of the protocol, developed in Section 4, is built upon these concepts.

The MAC protocols are classified into two categories: random access and controlled access. In the description of different MAC protocols to follow, a station with at least one message, waiting to be transmitted, is called *backlogged*; else it is *idle*.

In the *random access* scheme a station is allowed to transmit if the network medium is detected to be idle, and it can only be implemented on bus or star topologies with passive interfaces. While transmitting a message frame, the station continuously monitors the medium. If a transmitting station detects a collision, it immediately aborts the transmission to reschedule it after a random time based on the back-off algorithm. This

Acronyms

BAT = Bus Activity Timer
 BBS = Bidirectional Bus System
 BRAM = Broadcast Recognizing Access Method
 CAD = Computer-Aided Design
 CIM = Computer Integrated Manufacturing
 CSMA/CD = Carrier Sense Multiple Access with Collision Detection
 CSMA/CD-DCR = CSMA/CD with Deterministic Contention Resolution
 DAMA = Demand Assignment Multiple Access
 DSMA = Distributed Scheduling Conflict-Free Multiple Access
 FDDI = Fiber Distributed Data Interface
 L-R = Left-to-Right bus

MAC = Medium Access Control
 MAP = Manufacturing Automation Protocol
 Mbps = Megabits per second
 NRT = Non-Real-Time
 NRT-JAM = Jamming signal for NRT mode
 NRT-UJAM = Unjamming signal for NRT mode
 PT = Preemption Timer
 R-L = Right-to-Left bus
 RT = Real-Time
 RT-JAM = Jamming signal for RT mode
 RT-UJAM = Unjamming signal for RT mode
 TOP = Technical and Office Protocols
 UBS = Unidirectional Bus System
 UBS-RR = UBS with Round-Robin

access mechanism is called Carrier Sense Multiple Access with Collision Detection (CSMA/CD). An example is the IEEE 802.3 protocol that is used in TOP [3]. The performance (e.g., delay and throughput) of CSMA/CD decreases with increase in the ratio of the end-to-end propagation delay and the average time required to transmit a message frame. This phenomenon is significantly influenced by larger separation distances between communicating stations and increased channel bandwidth (for example, 100 Mbps in fiber optic media versus 10 Mbps in coaxial cables). Another drawback of CSMA/CD is the message frame must have a certain minimum length (which depends on the end-to-end propagation delay) to enforce collision detection [12]. This restriction degrades the performance when end-to-end propagation delay on the bus is larger than the designed packet transmission time.

The *controlled access*, also known as Demand Assignment Multiple Access (DAMA), schemes can be implemented with bus and ring topologies. The stations are ordered in a logical ring on the basis in which they are allowed to transmit any waiting message(s). The index number is the position of a station in the logical ring. The overhead due to round-trip propagation delay is minimal for the ring and unidirectional bus system (UBS) topologies in which the logical order of stations is identical to their physical order [12]. However, this is not true for bidirectional bus systems (BBS) where a station's index number does not necessarily conform to its physical order.

A controlled access scheme can be formulated using one of the two principles: Explicit Token Passing and Implicit Token Passing. In explicit token passing, a specific message, called *token*, is circulated around the logical ring and a station holding the token has the privilege to transmit. The station relinquishes this privilege by transmitting the token to the next station in the logical ring. Examples are the IEEE 802.4 Token Bus and IEEE 802.5 Token Ring. Although this access scheme has bounded packet delays for deterministic traffic, it undergoes the minimum delay due to ring latency, i.e., the time required for token circulation around the logical ring, and also suffers from protocol failures (such as loss or multiplicity of tokens) and the resulting delay due to the reinitialization.

In implicit token passing schemes, it is the stations that determine when to transmit on the basis of the activities in the medium [10]. Since the existence of an explicit token is not mandatory for operations of the protocol, robustness of this access scheme is expected to be superior to that of an explicit token access scheme. The delay is bounded and the throughput and data latency can be made less sensitive to end-to-end propagation delay. The implicit token passing schemes have been classified on the basis of their access mechanisms as: scheduling delay access, reservation access, and attempt-and-defer access [10].

Scheduling Delay Access Mechanism. This access mechanism is based upon staggering the potential starting time of individual stations, and is primarily suitable for BBS. The backlogged stations stagger their message end-to-end transmission by a *scheduling* delay which is a function of the propagation delay, the station's index number, and index number of the station that has just completed its transmission. Examples are BRAM [13] and L-Expressnet [14].

This distributed access control scheme is critically dependent upon accurate identification of the index number of each transmitting station by all other stations. Without the knowledge of the exact propagation delay between consecutively indexed stations, the scheduling delay is evaluated as a function of the end-to-end propagation delay. In high-speed fiber optic media, this delay reduces utilization of the medium and increases data latency. As a result, this access mechanism may not be suitable for fiber optic networks.

Reservation Access Mechanism. Reservation access mechanism uses global scheduling to assure conflict-free transmission [10]. It is primarily suitable for BBS in which a sub-channel or control wires are used (in addition to the main transmission medium for message transmission) to place reservations and select the next station by consensus. This selection is made according to a given measure such as relative positions or addresses of individual stations.

Although reservation access is primarily suitable for BBS, it can be implemented on UBS. In that case, the scheduling is achieved by unidirectionality of signal propagation and physical ordering of stations. Examples are DSMA [15] and UBS-RR [16]. Unidirectional signal propagation on the outbound channel of UBS establishes a logical order based on their physical order. This is similar to the signalling mechanism on the control wire in BBS. This scheme is suitable for fiber-optic-based networks but it is inefficient because of the large overhead in distributed networks where the end-to-end propagation delay is large.

Attempt-and-Defer Access Mechanism. This mechanism can only be implemented on UBS configuration with active or passive taps at a fiber optic medium, and the logical ring is formed in the physical order of stations. A backlogged station probes the status of the channel and, upon sensing the channel to be idle, it starts transmitting. If any activity from an upstream station is detected, the station immediately aborts its transmission and defers to the upstream transmission. In this way, stations experience a delay of t_d to detect a carrier signal. The detection delay causes an overlap in transmission before the station aborts its transmission. The overlap is limited to the initial t_d of the transmission time. If the message preamble is set to be greater than t_d , a message frame which has been completely transmitted by a station can be correctly received by all downstream stations. Therefore, in an asynchronous transmission, the loss of the first t_d in the preamble of a non-aborted transmission will not disrupt the synchronization process at the receivers [12]. On the other hand, in synchronous slotted transmission schemes, a backlogged station waits for the next slot and inspects the busy bit associated with it to determine if the slot has already been used. If the busy bit is not set, then it is set and the message is written into the slot; else the station waits for the next slot to start the access scheme over again. Examples are Expressnet [17], D-Net [18], Fasnet [19], U-Net [20], Tokenless Protocols [21], CSMA/CD-DCR [22], and Buzznet [12].

As stated above, the scheduling of access to the transmission medium is based on the order of the logical ring formed by the unidirectionality of signal propagation which, in turn, is determined by the physical location of stations. These schemes function in a controlled access mode, and the round-robin scheduling of access is established by implicit token passing. This access scheme is particularly suitable for fiber optic networks where the UBS configuration and implicit token passing make the access mechanism less sensitive to large end-to-end propagation delay and small packet transmission time.

Random access schemes like CSMA/CD are apparently more efficient than controlled access schemes at low offered traffic because of smaller overhead [22]. To utilize this advantage hybrid medium access protocols have been designed to operate in the random access mode at low traffic and switch over to the controlled access mode as the traffic increases. In this respect the attempt-and-defer access schemes are classified as pure forms and hybrid forms [10]. The improvement in the performance of such hybrid schemes is often questionable because random access delays and high data transmission schemes are prone to frequent collisions under large propagation delays which are prevalent in fiber optic media.

The Fiber Distributed Data Interface (FDDI) standard [23]

uses the token ring protocol at the transmission rate of 100 Mbps, and provides two classes of services, namely, synchronous and asynchronous. FDDI uses an optical fiber medium and is designed to serve up to 500 stations over an optical fiber path of length up to 100 kilometers. The need for high speed data communication by devices such as supercomputers and magnetic disc units has resulted in the development of FDDI. Token Ring access method, based on IEEE 802.5 standard, has been used as the access mechanism in FDDI. Three principal techniques may be implemented to improve the reliability of FDDI networks: Station bypass; Counter rotating rings; and Concentrator. Implementation of the priority scheme in FDDI is different from that of IEEE 802.5 standard. The stations monitor the token rotation time and, based on this time, the station may defer the transmission of low priority packets. This approach is called a *timed token rotation*.

Distributed Queue Dual Bus (DQDB) [24] uses a fixed size slot in data transmission, and the data is divided into short segments and desegmented at the destination station. In other words, data is transmitted in a frame relay manner. Although this approach is convenient for providing reserved connection-oriented slots, it has disadvantages for bursty traffic with duration of multiple slots. To provide fairness to all subscribers under distributed control, it is necessary to have rather complex request-counting procedures which may require extra hardware and/or software at each station. Furthermore, a station may have to issue many requests and have its message segmented into small packets that would arrive at the destination at irregular intervals. Consequently, the percent overhead becomes higher than necessary, and the efficiency and reliability of acknowledgement schemes are degraded. DQDB is under consideration for acceptance as a standard for Metropolitan Area Networks (MAN) by the IEEE 802.6 working group.

Current applications of fiber optics to networking are limited to point-to-point connections using star and ring topologies with active couplers where the MAC protocol is primarily based on imposed random access and explicit token passing. These limitations are primarily due to large attenuation caused by insertion of passive couplers, and are transitory from the perspectives of recent advances in fiber optic technology. The UBS architecture with active or passive couplers are implicit-token passing protocols is a viable option for fiber optic networks of the future.

3 Current Status of Networking in CIM

A typical network architecture currently used in manufacturing systems to serve rigid work cells is shown in Figure 1. The intra-cell devices are served by carrier band networks and the inter-cell communications take place via the broadband backbone network. As seen in Fig. 1, the data communication across two networks is supported by bridges and routers which are potentially 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 design and manufacturing system via a single high-speed medium is illustrated in Fig. 2. This architecture would potentially realize the concept of virtual cells to facilitate dynamic reallocation of resources. The advantages and disadvantages of the proposed networking concept in Figure 2 are discussed in [5].

The delay requirements of heterogeneous traffic in CIM networks have not been seriously considered in the design of these MAC protocols. In a manufacturing environment, network traffic can be broadly classified into two categories: real-

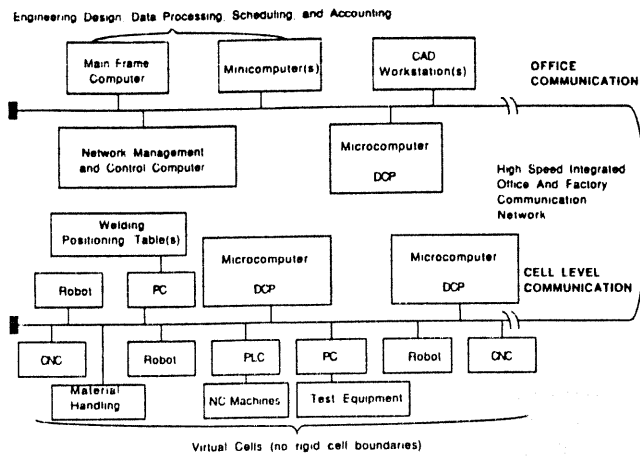


Fig. 2 Integrated networking concept for CIM

time and non-real-time. The real-time 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, real-time data transmission does not require the acknowledgement scheme [5]. On the other hand, non-real-time 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 non-real-time messages but the integrity of the data cannot be compromised. An acknowledgement scheme is required for non-real-time data transmission to ensure error free delivery. Real-time signals should be allowed to interrupt the non-real-time data transmission. The preemption will increase the data latency of non-real-time messages but will significantly increase the probability of timely delivery of real-time messages. Accurate delivery of all non-real-time 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 be highly reliable to ensure continuity of production, star topology may not be appropriate for CIM. On the other hand, ring topologies like 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 reinitialization in the event of token loss.

In view of the large number of subscribers and their dynamic configuration in an integrated manufacturing environment, the bus topology is considered to yield better performance in terms of delay, throughput, reliability, and operational flexibility than ring and star topologies. Unidirectionality of signal propagation makes fiber optic media suitable for adopting a dual-bus topology with the attempt-and-defer access mechanism [10, 12, 19-22] (also described in Section 2) which is, on the average, less susceptible to delays due to signal detection and propagation than the scheduling delay access mechanism associated with the bidirectional bus topology [10].

Baseband Technical & 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, the performance in terms of throughput and data latency significantly deteriorates as the ratio of propagation delay to packet transmission time increases [9]. 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 [7] 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 [10]. 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 implicit token passing [10]. Buzznet [12] is apparently superior to all other fiber-optic-based hybrid protocols developed so far. 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 as it is for fiber optics in the CIM environment. This will result in diminished performance due to repeated switching between the random access and controlled access modes. Since heterogeneous data traffic in the CIM environment consists of real-time and non-real-time data traffic [5] and Buzznet does not have a built-in priority scheme, real-time messages will encounter large delays.

It is highly desirable for a CIM network to have a fault-accommodating architecture with the capability of self repair. This feature can be realized by a dual-bus UBS network (with active or passive taps) where detection of a station transmission also identifies whether the index number of the source station is greater than or less than that of the station detecting the location is of transmission. The capability for unique identification of the source station would be very useful for network fault diagnostics and isolation. A malfunctioning station not adhering to the access schedule mechanism can be autonomously isolated to make self repair of the network possible.

4 Description of the Proposed Protocol

Unidirectional dual bus topology has been adopted in the proposed MAC layer protocol where the left-to-right and right-to-left buses are denoted as L-R and R-L, respectively. The protocol is formulated using the concept of Buzznet's controlled access mode [9], and is designed to have the following major features.

- Accommodation of heterogeneous traffic of the CIM environment within a single network medium; and
- Built-in prioritization of real-time 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

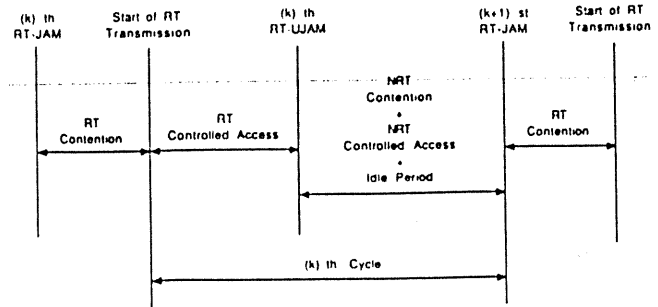


Fig. 3 Time diagram of RT and NRT modes

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 equipped two times to control the bus operations under RT and NRT modes:

Bus Activity Timer (BAT) is started if both buses are sensed idle. If any activity is detected within R , where R is 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 possible located at an upper layer.

Remark 1: The role of the preemption timer α is, to some extent, analogous to that of the target token rotation times (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 as it is for multi-robot control systems in inter-cell operations. ■

The operations of the proposed protocol at a given station, as illustrated in Fig. 3, are classified as follows:

Contention Phase is the process of scheduling both RT and NRT message transmissions.

Controlled Access Phase follows the contention phase and is the process of transmitting both RT and NRT message(s).

RT Cycle is the interval between the end of the RT contention phase and the instant of sensing RT unjamming or BAT expiration.

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 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. 3.

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

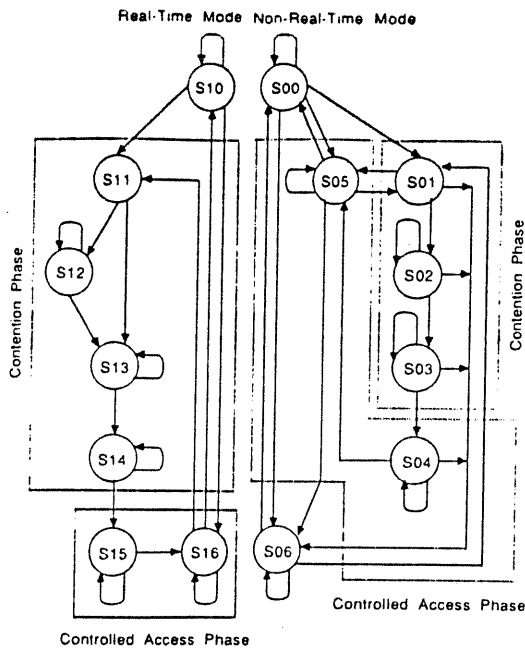


Fig. 4 Finite state machine model

if the PT or BAT is expired, or if it detects RT-JAM. In the contention phase, the stations with backlogged RT message(s) establish a logical ring for the implicit token passing mechanism. 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 message 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 acknowledgement 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.

4.1 Finite State Machine Model of the Protocol. The access mechanism for the two modes is represented by a finite state machine model which consists of two isolated but interdependent and concurrently executing submodels for the RT and NRT modes as shown in Figure 4. Every station is assumed to have two buffers, one for RT and the other for NRT. Thus a station may be backlogged in both or one of these two modes at any instant. However, network design criteria may limit the average number of backlogged RT messages such that their transmission does not exceed a specified fraction of the overall network bandwidth. This fraction depends on several criteria that include:

- Bounds of data latency for different classes of RT messages, and number and length of messages in each class;
- Maximum length of NRT messages; and
- Network bandwidth and end-to-end propagation delay.

The nomenclature and terminology, associated with the finite state machine model of the protocol, are given below.

A state is represented by S_{xy} , where x is the type of access mode: $x=1 \Rightarrow$ RT and $x=0 \Rightarrow$ NRT; and y denotes the state number within a particular access mode.

4.1.1 Logical Variables for Protocol Operations at a Station

- BA_T:** Running state of BAT and the station not transmitting;
- P_T:** Running state of PT;
- RT_BUF:** RT buffer of the station non-empty;
- RT_DORMANT:** No backlogged RT message at the instant of sensing RT-JAM;
- RT_JAM:** RT-JAM sensed or initiated at the instant of the observation;
- RT_JAM(2R):** A period of $2R$ elapsed after occurrence of RT-JAM where R is the round-trip propagation delay;
- RT_JAM(ℓ):** A period of $\ell \in (0, R]$ is elapsed after RT_JAM($2R$);
- RT_TX:** Complete transmission of backlogged RT message(s) at a station;
- RT_UJAM:** RT-UJAM sensed or initiated at the instant of the observation;
- NRT_BUF:** NRT buffer of the station non-empty;
- NRT_JAM:** NRT-JAM sensed or initiated at the instant of the observation;
- NRT_JAM(R):** A period of R has elapsed after occurrence of NRT-JAM;
- NRT_JAM(ℓ):** A period of ℓ has elapsed after NRT_JAM(R);
- NRT_TX:** Complete transmission of backlogged NRT message(s) at a station;
- NRT_UJAM:** NRT-UJAM sensed or initiated at the instant of the observation.

Remark 3: $RT_JAM(2R)$ implies that, during this period of $2R$, the station transmits RT-JAM on both buses, deferring to upstream RT-JAM transmissions. Similarly, $NRT_JAM(R)$ implies that, during this period of R , the station transmits NRT-JAM on both buses, deferring to upstream RT-JAM and NRT-JAM transmissions. ■

Remark 4: $RT_JAM(\ell)$ implies that, during this period of $\ell \in (0, R]$, the station transmits RT-JAM only on L-R, deferring to upstream RT-JAM transmissions. Similarly, $NRT_JAM(\ell)$ implies that, during this period of ℓ , the station transmits NRT-JAM only on L-R, deferring to upstream RT-JAM and NRT-JAM transmissions. ■

4.1.2 State Description of RT Finite State Machine Submodel.

- $S_{10}: RT_BUF \cap \overline{RT_JAM}$
- $S_{11}: RT_BUF \cap \overline{RT_JAM} \cap P_T$
- $S_{12}: BA_T \cap RT_BUF \cap \overline{RT_JAM} \cap P_T$
- $S_{13}: (BA_T \cup P_T \cup RT_JAM) \cap RT_BUF$
- $S_{14}: (RT_JAM(2R) \cap \overline{RT_JAM}) \cap RT_BUF$
- $S_{15}: RT_JAM(\ell) \cap RT_BUF$
- $S_{16}: (RT_DORMANT \cup \overline{(RT_DORMANT \cap RT_TX)}) \cap RT_UJAM \cap BA_T$

Remark 5: A station in the state S_{13} transmits RT-JAM on both buses for a period of $2R$. If no RT-JAM is detected from any upstream station on L-R (or R-L), then the station identifies itself to be in the leftmost (or rightmost) active position. Normally a period of R is sufficient to detect RT-JAM. The additional R is required to preempt an ongoing NRT mode when any other station is transmitting NRT-JAM. ■

Remark 6: A station in the state S_{14} attempts to transmit RT-JAM only on L-R deferring to any upstream RT-JAM, and remains in this state for a period of $\ell \in (0, R]$ where ℓ is a

function of the number of RT stations in the contention phase, their relative locations, and the instants of entering the contention phase. ■

Remark 7: A station in the state S_{15} transmits RT messages using a *nongated* scheme. Upon sensing L-R to be inactive, the station starts transmitting the preamble on L-R only and simultaneously senses it for a period of the station response time t_d . If any upstream transmission is detected, it defers and resumes probing L-R. The process is repeated if L-R is sensed idle. If the station does not detect an upstream transmission on L-R within t_d , the preamble is transmitted on both buses followed by its backlogged message. On successful completion of its transmission, the station checks if it is the rightmost active station. If so, it transmits RT-UJAM on both buses. The above access mechanism requires the message to be simultaneously transmitted on both buses even though the station has a knowledge of the bus on which the destination is a downstream station. This is apparently a wastage of the medium bandwidth. A solution to improve the bandwidth utilization for the above access scheme is discussed later in this section. ■

Remark 8: At the state S_{16} , the stations with backlogged RT message(s) and $RT_DORMANT$ probe L-R for an end-of-carrier (EOC) signal. If EOC is sensed and R-L is idle, then the station attempts to transmit the waiting RT message. ■

4.1.3 State Description of NRT Finite State Machine Sub-model

$$\begin{aligned} S_{00}: & (\overline{NRT_BUF} \cap \overline{NRT_JAM}) \cap \overline{RT_JAM} \\ S_{01}: & (\overline{NRT_BUF} \cap \overline{NRT_JAM}) \cap \overline{RT_JAM} \\ S_{02}: & (\overline{NRT_BUF} \cap \overline{NRT_TX}) \cap \overline{RT_JAM} \\ S_{03}: & (\overline{NRT_BUF} \cap \overline{NRT_TX} \cap \overline{NRT_JAM}(R) \\ & \cap \overline{NRT_JAM}) \cap \overline{RT_JAM} \\ S_{04}: & (\overline{NRT_BUF} \cap \overline{NRT_TX} \cap \overline{NRT_JAM}(\ell) \\ & \cap \overline{RT_JAM}) \\ S_{05}: & (\overline{NRT_TX} \cap \overline{NRT_JAM}) \cap (\overline{NRT_UJAM} \cup \\ & \overline{BA_T}) \cap \overline{RT_JAM} \\ S_{06}: & \overline{RT_JAM} \cap (\overline{RT_UJAM} \cup \overline{BA_T}) \end{aligned}$$

Remark 9: A station in the state S_{02} transmits NRT-JAM on both buses for a period of R and must defer to RT-JAM. If no NRT-JAM is detected from any upstream station on L-R (or R-L), then the station identifies itself to be in the leftmost (or rightmost) active position. ■

Remark 10: A station in the state S_{03} attempts to transmit NRT-JAM only on L-R deferring to any upstream transmission, and remains in S_{03} for a period of $\ell \in (0, R]$ where ℓ is a function of the number of NRT stations in the contention phase, their relative locations and the instants of entering the contention phase. ■

Remark 11: The messages in NRT mode are transmitted in the gated scheme. The attempt & defer access mechanism in the state S_{04} is similar to that in S_{15} . ■

4.1.4 Description of RT Finite State Transitions

$$\begin{aligned} S_{10}/S_{10}: & \overline{RT_BUF} \cap \overline{RT_JAM} \\ S_{10}/S_{11}: & \overline{RT_BUF} \\ S_{10}/S_{16}: & \overline{RT_JAM} \\ S_{11}/S_{12}: & \overline{BA_T} \\ S_{11}/S_{13}: & \overline{BA_T} \\ S_{12}/S_{12}: & \overline{BA_T} \cap \overline{RT_JAM} \\ S_{12}/S_{13}: & \overline{BA_T} \cup \overline{RT_JAM} \\ S_{13}/S_{13}: & \overline{RT_JAM}(2R) \\ S_{13}/S_{14}: & \overline{RT_JAM}(2R) \\ S_{14}/S_{14}: & \overline{RT_JAM}(\ell) \\ S_{14}/S_{15}: & \overline{RT_JAM}(\ell) \end{aligned}$$

$$\begin{aligned} S_{15}/S_{15}: & \overline{RT_TX} \\ S_{15}/S_{16}: & \overline{RT_TX} \\ S_{16}/S_{16}: & \overline{RT_UJAM} \cap \overline{BA_T} \\ S_{16}/S_{10}: & \overline{RT_BUF} \cap (\overline{RT_UJAM} \cup \overline{BA_T}) \\ S_{16}/S_{11}: & \overline{RT_BUF} \cap (\overline{RT_UJAM} \cup \overline{BA_T}) \end{aligned}$$

4.1.5 Description of NRT Finite State Transitions

$$\begin{aligned} S_{00}/S_{00}: & (\overline{NRT_BUF} \cap \overline{NRT_JAM}) \cap \overline{RT_JAM} \\ S_{00}/S_{01}: & \overline{NRT_BUF} \\ S_{00}/S_{05}: & \overline{NRT_JAM} \\ S_{00}/S_{06}: & \overline{RT_JAM} \\ S_{01}/S_{02}: & \overline{NRT_TX} \\ S_{01}/S_{05}: & \overline{NRT_TX} \\ S_{01}/S_{06}: & \overline{RT_JAM} \\ S_{02}/S_{02}: & \overline{NRT_JAM}(R) \\ S_{02}/S_{03}: & \overline{NRT_JAM}(R) \\ S_{02}/S_{06}: & \overline{RT_JAM} \\ S_{03}/S_{03}: & \overline{NRT_JAM}(\ell) \\ S_{03}/S_{04}: & \overline{NRT_JAM}(\ell) \\ S_{03}/S_{06}: & \overline{RT_JAM} \\ S_{04}/S_{04}: & \overline{NRT_TX} \\ S_{04}/S_{05}: & \overline{NRT_TX} \\ S_{04}/S_{06}: & \overline{RT_JAM} \\ S_{05}/S_{10}: & \overline{NRT_BUF} \cap (\overline{NRT_UJAM} \cup \overline{BA_T}) \\ S_{05}/S_{01}: & \overline{NRT_BUF} \cap (\overline{NRT_UJAM} \cup \overline{BA_T}) \\ S_{05}/S_{05}: & (\overline{NRT_UJAM} \cap \overline{BA_T}) \cap \overline{RT_JAM} \\ S_{05}/S_{06}: & \overline{RT_JAM} \\ S_{06}/S_{06}: & \overline{NRT_BUF} \cap (\overline{RT_UJAM} \cup \overline{BA_T}) \\ S_{06}/S_{01}: & \overline{NRT_BUF} \cap (\overline{RT_UJAM} \cup \overline{BA_T}) \\ S_{06}/S_{06}: & \overline{RT_UJAM} \cap \overline{BA_T} \end{aligned}$$

4.2 Improvement of Channel Bandwidth Utilization. In the above protocol a message is simultaneously transmitted on both buses to keep them busy, resulting in under-utilization of the channel bandwidth. This scheme has been used in U-Net and Buzznet under the assumption that the physical location of the destination station is unknown. However, the physical address in the UBS being identical to the station's index number in the logical ring, the source station needs to transmit the message only on the bus in which the destination is a downstream station. A discussion on how the proposed protocol can be modified to improve the medium utilization follows.

During the transmission of a long NRT message, the medium utilization can be improved by transmitting any RT message(s) or other short NRT message(s) whose destination lie on the opposite bus and the total transmission time is smaller than that of the NRT message. This result in improved performance of the protocol in terms of better medium utilization and smaller data latency. This modification does not require any significant change in the protocol structure.

5 Summary and Conclusions

The CIM network protocol has been developed using the unidirectional dual bus architecture to take advantage of the unique features of optical fibers as the network media. The proposed protocol architecture allows high-speed and reliable communications of heterogeneous traffic in the integrated office and factory environments within a common network medium. This largely eliminates the need for inter-net communications via bridges and routers which are sources of potential delay and congestion. Furthermore the use of a common medium should enhance inter-cell communications on the factory floor and facilitate formation of virtual cells for flexible manufacturing.

This protocol can be readily adopted to the fiber-optic-based version of MAP and TOP with practically no changes in the

IEEE 802.2 logical link control (LLC) and upper layers. This will make the specifications of MAP and TOP identical up to the presentation layer; only the application layer which is user-specific could be different.

The proposed protocol is described in detail in this first part. The second part [4] presents the performance analysis of this protocol using a statistical model, and a comparison of the simulation and analytical results.

References

- 1 Ray, A. and Poha, S., "Research Directions in Networking for Manufacturing Systems," *ASME Journal of Engineering for Industry*, Vol. 111, No. 2, May 1989, pp. 109-115.
- 2 *Manufacturing Automation Protocol (MAP) 3.0 Implementation Release*, Available through MAP/TOP Users Group, One SME Drive P.O. Box 930, Dearborn, MI 48121.
- 3 *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.
- 4 Ayyagari, A. and Ray, A., "A Fiber-Optic-Based Protocol for Manufacturing System Networks: Part II—Statistical Analysis and Discrete-Event Simulation," published in this issue, pp. 121-131.
- 5 Ray, A., "Networking for Computer-Integrated Manufacturing," *IEEE Network*, Vol. 2, No. 3, May 1988, pp. 40-47.
- 6 Bergmann, F. E., "Fiber Optic as a Physical Layer for MAP," *IEEE INFOCOM'87*, Mar. 1987, pp. 64-69.
- 7 Moustakas, S., "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.
- 8 Wright, P. K., and Bourne, D. A., *Manufacturing Intelligence*, Addison-Wesley Publishing Company, Reading, MA, 1988.
- 9 Stallings, W., *Data and Computer Communications*, Macmillan Publishing Company, New York, 1985.
- 10 Fine, M., and Tobagi F. A., "Demand Assignment Multiple Access Schemes in Broadcast Bus Local Area Networks," *IEEE Trans. Computers*, Vol. C-33, No. 12, Dec. 1984, pp. 1130-1159.
- 11 Tobagi, F. A. and Hunt, V. B., "Performance Analysis of Carrier Sense Multiple Access with Collision Detection," *Computer Networks*, Vol. 4, No. 5, Oct./Nov. 1980, pp. 245-259.
- 12 Gerla, M., Wang, G., and Rodrigues, P., Buzz-Net: A Hybrid Token/Random Access LAN," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 6, July 1987, pp. 977-988.
- 13 Chlamtac, I., Franta, W. R. and Levin, K.D., "BRAM: The Broadcast Recognizing Access Method," *IEEE Trans. Commun.*, Vol. COM-27, No. 8, Aug. 1979, pp. 1183-1189.
- 14 Borgonovo, F., Fratta, L., Tarini, F. and Zini, P., "L-Expressnet: A Communication Protocol for Local Area Networks," *IEEE INFOCOM'83*, San Diego, CA, Apr. 1983.
- 15 Mark, J. W., "Distributed Scheduling Conflict-Free Multiple Access for Local Area Communication Networks," *IEEE Trans. Commun.*, Vol. COM-28, No. 12, Dec. 1980, pp. 1968-1976.
- 16 Rom, R., and Tobagi, F. A., "Message-Based Priority Functions in Local Multiaccess Communication Systems," *Computer Networks*, Vol. 5, No. 4, July 1981, pp. 273-286.
- 17 Tobagi, F. A., Borgonovo, F., and Fatta, L., "Expressnet: A High-Performance Integrated-Sevices Local Area Network," *IEEE Journal on Selected Areas in Commun.*, Vol. SAC-1, No. 5, Nov. 1983, pp. 898-913.
- 18 Tseng, C., and Chen, B., "D-Net, A New Scheme for High Data Rate Optical Area Networks," *IEEE Journal on Selected Areas in Commun.*, Vol. SAC-1, No. 3, Apr. 1983, pp. 493-499.
- 19 Limb, J. O., and Flamm, L. E., "A Distributed Local Area Network Packet Protocol for Combined Voice and Data Transmission," *IEEE Journal on Selected Areas in Commun.*, Vol SAC-1, No. 5, Nov. 1983, pp. 926-934.
- 20 Gerla, M., Rodrigues, C. and Yeh, C., "U-Net: A Unidirectional Fiber Bus Network," *FOC/LAN 84 The Eight International Fiber Optics Communications & Local Area Networks Exposition*, Las Vegas, NV, Sept. 19-21, 1984, pp. 295-299.
- 21 Rodrigues, P., Fratta, L., and Gerla, M., "Tokenless Protocols for Fiber Optic Local Area Networks," *IEEE Journal on Selected Areas in Commun.*, Vol. SAC-3, No. 6, Nov. 1985, pp. 928-940.
- 22 Takagi, A., Yamada, S. and Sugawara, S., "CSMA/CD with Deterministic Contention Resolution," *IEEE Journal on Selected Areas in Commun.*, Vol. SAC-1, No. 5, Nov. 1983, pp. 877-884.
- 23 Dykeman, D. and Bux, W., "Analysis and Tuning of the FDDI Media Access Control Protocol," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-6, No. 6, Jul. 1988, pp. 997-1010.
- 24 Davids, P., and Martini, P., "Performance Analysis of DQDB," *IEEE Proceedings: Ninth Annual International Phoenix Conference on Computers and Communications*, March 1990, pp. 548-555.