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Chia Shen, *Member*, *IEEE*, and Ichiro Mizunuma, *Member*, *IEEE Computer Society*

Abstract—In this paper, we propose and present Real-Time Channel-based Reflective Memory (RT-CRM)—a useful programming model and middleware communication service for constructing distributed real-time applications on commercially available open systems. RT-CRM provides remote real-time data reflection abstraction using a simple writer-push model. This writer-push approach enables us to easily decouple the QoS characteristics of the writers from that of the readers. This decoupling is crucial in supporting different kinds of remote data transfer and access needs that one often finds in distributed real-time systems. We will describe the design of RT-CRM, along with a set of easy-to-use API to access the RT-CRM service. We have implemented RT-CRM as part of a larger real-time middleware project, MidART. We address many of the important implementation issues, including buffer management and QoS support. We demonstrate the feasiblity of RT-CRM through a discussion of our application programming support and performance data.

Index Terms—Real-time communication service, data distribution, monitor and control, distributed real-time systems.

1 Introduction

It is becoming ever more important for both industry and academia to design distributed real-time systems using open, standard, commercially available computers and networks. This is largely due to 1) network and processor technology advances, 2) cost considerations, and 3) the desire for easy system integration and evolution. Currently, there is no network middleware for open standard networks and operating systems for real-time applications. Existing systems are largely proprietary. On the other hand, socket interface is cumbersome and difficult to use for application builders. Moreover, real-time applications need end-to-end quality of service provision. To facilitate the construction of distributed real-time applications on open off-the-shelf systems, we must first provide easy-to-use real-time programming models and services to the real-time application designers.

In this paper, we propose and present Real-Time Channel-based Reflective Memory (RT-CRM)[1]—a useful programming model and middleware communication service [14] for constructing distributed real-time applications on commercially available open systems. The class of applications we are dealing with are those in which humans need to interact (e.g., control and monitoring) with instruments and devices in a networked environment through computer-based interfaces. Examples of such applications include distributed industrial plant control systems, multimachine surgical simulation systems, virtual labs, and large telescope control systems.

We have designed and implemented RT-CRM as part of an ongoing project *MidART—Mid*dleware and network *A* rchitecture for distributed *R* eal-*T*ime industrial systems [10], [8]. MidART provides a set of communication facilities for building networked real-time applications.

Fig. 1 is an example of the application environment. The characteristics of the class of distributed real-time applications for which RT-CRM is designed for and their implications for the requirements of the underlying real-time system and communication support are:

1. The most frequent communication and data sharing patterns are many-to-one communication for monitoring and point-to-point for control. For example, a LAN-based industrial plant has hundreds of plant control sensors, but only a handful, usually five to 10, operator stations. Therefore, the dominant type of data distribution can be viewed as many-to-one in nature, instead of the common one-to-many multicast model.
2. The monitoring and control interaction between the operators and the controlled system can be decoupled into unidirectional channels, e.g., the data from one or more physical devices are sent from the devices to the operator stations, and control data is sent from an operator station to a device controller.
3. Not all the data need to be periodically broadcast to all the nodes in the network all the time. Typically, there are many producers/writers, each producing their respective, separate data or video, while a consumer/reader will need data from a subset of these producers. The members of this subset are not

1. RT-CRM actually should be read as Real-Time *and* Channel-based Reflective Memory and is not based on real-time channels [6], although real-time channels can be one of the underlying communication support to implement RT-CRM.

• *C. Shen is with Mitsubishi Electric Research Labs (MERL), Cambridge Research Lab, 201 Broadway, Cambridge, MA 02139. E-mail: shen@merl.com.*
• *I. Mizunuma is with the Industrial Electronics and Systems Lab., Mitsubishi Electric Corp., 8-1-1, Tsukaguchi-honmachi, Amagasaki, Hyogo, 661-8661, Japan. E-mail: mizunuma@con.sdl.melco.co.jp.*

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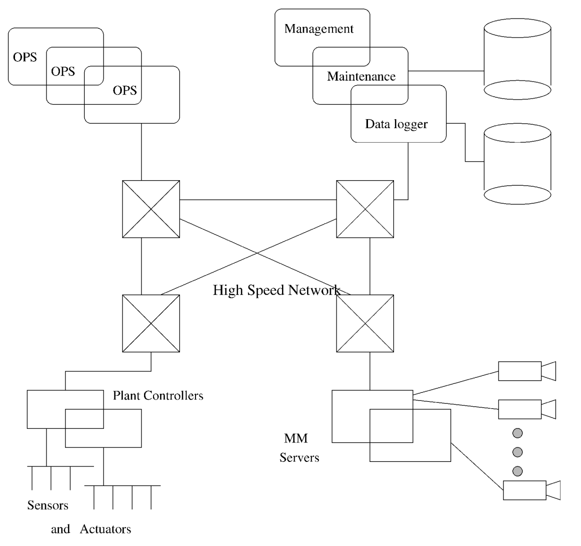

Fig. 1. An example industrial plant system with high speed networks. OPS = Operator Stations.

fixed and will change from time to time, whenever a reader requests to do so.

4. Human operators choose what data to view and to review. Historical data are often requested by the operators. These data enable the operators to review past activities in the system. This history data should be retrieved in real-time and with response time small enough to support interactive display of past and present sensory information. This characteristic has two important implications. The first is that this kind of history data is needed only for the recent past, but may be requested very frequently. The second implication is that, since the sensory data are not immediately "consumed," we need to support both the constant data generation and collection from the devices and the frequent reviewing of historical data simultaneously.
5. QoS (Quality of Service) in terms of bounded message delay on sensory data updates and control message delivery is required. The delay bound requirements usually range from a few milliseconds to a couple hundreds of milliseconds.
6. Physical devices, such as controllers, instruments, and digital cameras, are simple computers with limited computation and storage capacity, while operator stations and multimedia servers have the capability to perform sophisticated functions and have more memory and disk capacity. This implies that we need to provide very simple and efficient data transport and communication services to be used by the physical devices.
7. Distributed real-time applications are long-lived—they need support for plug-and-play type of system construction and evolution.

While most of the current research focuses on real-time message communication, as examplified in [6], [9], [13], after analyzing the characteristics of the applications, we have approached the problem from a memory-to-memory data transfer perspective. This enabled us to devise a useful real-time distributed programming model and to provide a set of intuitive middleware services. The concept of RT-CRM is based on four principles:

- To provide data reflection with guaranteed timeliness to distributed real-time applications. We define *data reflection* as the memory-to-memory data transfer between remote hosts in a networked environment.
- To provide flexibility in how, what, and when data are reflected.
- To keep the information servers (be it an instrument or device or an industrial plant controller) as simple as possible—only to perform the necessary data reflection.
- To enable the construction of a distributed real-time system in a plug-and-play fashion and to give the application designer an easy-to-use interface.

RT-CRM supports these principles based on two key properties: 1) a "writer-push" data reflection model and 2) the decoupling of writers' and readers' QoS. The simplicity of a writer-push data reflection model makes it easier to provide predictability with flexibility in the fashion (e.g., synchronous vs. asynchronous) in which the data are reflected onto remote nodes. This should be attractive to real-time applications. Moreover, it also supports video transmission naturally. One should be able to use RT-CRM for both traditional data/control communication, as well as multimedia (video, audio, image) communication. The writer-push model enables many higher level functions, such as displaying the history of plant monitoring data or setting control values, to have simple designs where most of the computation only occurs on the reader's node.

There has been a lot of real-time research addressing the issue of providing end-to-end delay guarantee. End-to-end in a networked environment can mean many things to an application. We classify end-to-end into three different levels—Application-to-application (AtA), memory-to-memory (MtM), and network interface-to-network interface (NtN). AtA is where the guarantee is provided from the moment the sending application generates the data to the moment the receiving application retrieves the data. MtM is where the guarantee is provided from the moment when the data is taken from the sending host memory to the moment when the data is deposited into the receiving host memory, regardless of when the data is generated by the sending application and when the receiving application actually retrieves the data. NtN is simply the network guarantee from when the data is transmitted from the sending network interface to when the data is entirely received by the receiving network interface. We have discovered that different application scenarios require different levels of end-to-end guarantee. We have designed

RT-CRM to allow the application to choose between AtA and MtM according to its own requirement.[2]

We implemented the first prototype of RT-CRM over an ATM LAN with one FORE Systems ATM switch connecting PCs running QNX on which we emulated sample operator workstations and plant controllers. Our preliminary performance tests show that RT-CRM incurs very little overhead and is a feasible solution for real-time plant monitoring and control applications. Currently, we are also implementing RT-CRM on a Switched Fast Ethernet-based system with Pentium Pro PCs running Windows NT 4.0.

The rest of the paper is organized as follows: We discuss related remote memory systems and their limitations in Section 2. Section 3 gives the detailed architecture design of RT-CRM. We have implemented a set of API which provide programming access to the RT-CRM middleware service. These APIs and application programming support are also described in Section 3. In Section 4, we address important implementation issues of RT-CRM. These include 1) concurrency control and synchronization and 2) buffer management schemes and a proof for the minimum number of buffers needed to avoid locking for readers of the reflective memory. Section 5 discusses QoS and network interface support issues that are both closely related to the design and implementation of RT-CRM. Performance in terms of end-to-end latency, comparisons with IP via socket interface, and some API overhead are shown in Section 6. The paper concludes in Section 7.

2 Related Work on Remote Memory Systems

In this section, we discuss existing remote memory systems.[3] In particular, we point out their limitations for supporting the type of real-time applications under consideration.

2.1 Why Not Distributed Shared Memory?

Distributed shared memory provides transparent reads and writes of shared data in a networked environment. However, we do not need the full semantics of a DSM system such as those found in the TreadMarks DSM system described in [2]. Most of the functionalities of a DSM system are built to provide an illusion of a global virtual memory and to support concurrent writes on different nodes, e.g., a read must return the value that is last written. Thus, a DSM system must implement functions to deal with 1) managing local process page faults while the physical page last written is on a remote site, 2) coherency protocols, such as invalidation for replicated copies, 3) consistency model, e.g., sequential consistency, eager, or lazy release consistency.

The distributed real-time application domain does not require this full set of DSM semantic support. For example, we do not need the invalidation process at all. Our data in general is updated either periodically or upon a change of value. In either case, the reader usually can read the latest copy on its local processor. Synchronization only needs to occur when the local copy is being actually updated. More importantly, full DSM support will magnify many worst case delay bounds for data updates where multiple writers/multiple readers issue writes and reads. In a real-time system, we must consider this worst case delay.

2.2 Why Not Reflective Memory?

Hardware supported reflective memory, such as what is provided by SCRAMNet of VME Microsystems, Inc. [16], replicates (or reflects) data in all nodes of the network in a bounded amount of time (e.g., 1usec/node latency). These reflective memory systems, based on a ring topology, can only support a limited physical memory size, typically 1 to 16 MByte, and a limited number of nodes (up to 256). These hardware reflective memory systems are very expensive. Since we do not need to distribute data to all the nodes all the time, reflective memory will greatly limit the amount of actual memory we can support. For example, for an N-node system, we need $K * N$ system memory, assuming each node needs to reflect data of size K.

2.3 Why Not Memory Channels?

Memory Channel is a hardware-software combined technology from Digital Equipment Corp., originally licensed from Encore Computer Corp [7]. It is designed for low latency high performance clustered parallel computing and is in the middle ground as far as performance and scalability are concerned between symmetric multiprocessors and ATM. A Memory Channel is shared. Reads and writes on a Memory Channel are supported directly by DEC's PCI-MC adaptors. For writes, the adaptor can send writes to a single node, or multiple nodes, on a per page basis. Reads are supported via nonswappable physical memory—the adaptor can DMA incoming data with a known shared address space map into the corresponding physical memory.

Memory Channel can only support a limited number of nodes (up to eight AlphaServers) and a limited distance (three-meter link from the Memory Channel Hub to a server). Although Memory Channel is a useful concept, we need to support, potentially, up to hundreds of nodes in a network and we need data updates (i.e., data reflection) with specifiable time bounds and frequency.

In summary, our Real-Time Channel-based Reflective Memory is much more flexible compared with either hardware supported reflective memory and memory channels or software supported distributed shared memory. In hardware supported reflective memory, the data is reflected *immediately* in a bounded amount of time to other nodes as soon as the writer application deposits its new data. In distributed shared memory, the new data is made available to other readers or writers with one of two methods: either upon data release or upon data acquisition. There is no time constraint guarantee associated with either of these methods. In RT-CRM, we allow the reader application to specify *when* it wants the data to be reflected and we guarantee the timeliness of this reflection using a real-time writer-push model.

2. Note that, with a good network interface hardware technology such as those found in [11], one can narrow the gap between MtM and NtN. However, this is beyond the scope of our work reported here.

3. DSM, Reflective Memory, and Memory Channels, at some level, are all systems and protocols which allow reads and writes on physically distant memories in a networked environment. Thus, we call them *Remote Memory Systems*. DSM is a higher level protocol than both Reflective Memory and Memory Channels, but still provides remote memory services.

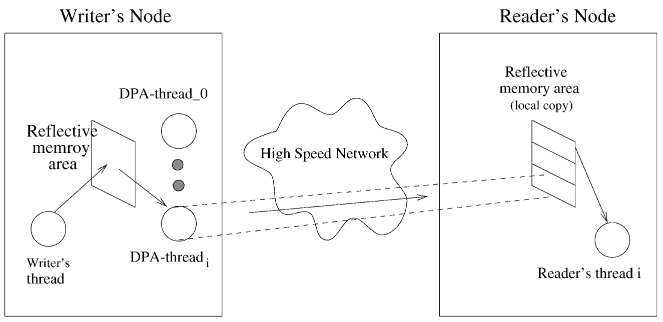

Fig. 2. RT-CRM high level architecture.

3 RT-CRM: Design, API, and Application Programming Support

3.1 Overview of RT-CRM

In Real-Time Channel-based Reflective Memory (RT-CRM), we combine the benefits from 1) Reflective Memory (i.e., updates propagated in bounded amount of time), 2) Memory Channel (i.e., hardware assisted, virtual connection-based memory to memory transfer of data), and 3) open standard high speed networks such as ATM and Fast Ethernet. The *unidirectional* access pattern and bounded update reflection time of the applications require *reflective*, rather than *shared*, memory semantics. To eliminate the lack of scalability problem in traditional Reflective Memory, we use the concept of channels.

In a distributed real-time monitoring and control system, we require applications to specify, at memory channel establishment time, 1) *who* needs the data, and 2) *when or how often* a reader needs the data. The schedulability or admissibility of read and write operations can be determined. This allows RT-CRM to use a writer-push (vs. a reader-pull) underlying model in which data produced remotely will be actively pushed through the network and written into a reader's memory without the reader explicitly requesting the data at run time.

Fig. 2 depicts the high level architecture of RT-CRM. RT-CRM is an association between a writer's memory and a reader's memory on two different nodes in a network with a set of protocols for memory channel establishment and data update transfer. A writer has a memory area where it stores its current data, while a reader establishes a similar memory area on its own local node to receive the data reflected from the writer. Data reflection is accomplished by a data push agent thread, a DPA-thread, residing on the writer's node and sharing the writer's memory area. This agent thread represents the reader's QoS and data reflection requirements. A virtual channel is established between the agent thread and the reader's memory area through which the writer's data is actively transmitted and written into the reader's local memory area. In this architecture, we support the following features:

- A reader memory area may be connected to multiple remote writer memory areas simultaneously. However, at any moment, only one writer is permitted to write into the reader's memory area via the associated agent thread.

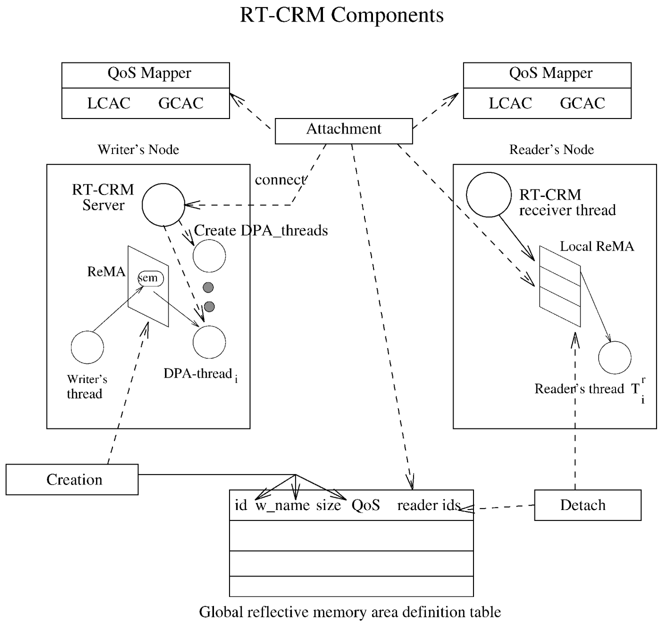

Fig. 3. Reflected memory area, threads, and system tables in RT-CRM.

- A writer memory area may be connected to many remote reader memory areas simultaneously. There can be many data push agent threads representing many readers associated with the same writer memory area.

These features enable us to satisfy the application requirements described in Section 1, yet minimize the complexity of the design on the writer's node. The writer only needs to deposit its data into the designated memory area, while all the other more complicated operations and QoS support are handled by the data push agent threads and the readers. In essence, RT-CRM is a distributed programming service provided in MidART. Many other more sophisticated or useful application functions, such as histories of data, continuous video, and video alarm, can be built on top of this service.

3.2 Detailed Design of RT-CRM

Fig. 3 illustrates the key components and operations of RT-CRM. Discussions throughout this section will refer to the figure. A RT-CRM consists of:

1. a writer thread that updates the reflective memory area periodically according to the writer's QoS,
2. a reflective memory area (ReMA) owned by the writer node,
3. a set of QoS parameters,
4. a semaphore (sem) with priority inheritance,
5. one or more data push agent threads, DPA_threads, one for each reader connection, defined by readers QoS parameters,
6. one or more receiver threads on the reader's node if direct memory access from a network interface if not available, and
7. a set of one or more readers, each of which has a local copy of the ReMA.

Note that the writer and the reader threads are applications threads, thus they are not really part of RT-CRM.

3.2.1 Creation

We allow a ReMA to be created by either a writer or a reader. This flexibility is necessary to support a LAN-based real-time application where nodes may join and leave dynamically and new data may be requested to be added into the system by any node. At creation time, each reflective memory area is associated with a global id, a size, QoS in terms of update period/frequency, and a semaphore for read-write conflict resolution on the writer's node. This information is initialized in the reflective memory area definition table. The table is a network-wide global table, allowing all potential readers and writers to know what the QoS/period of the writer is for this reflective memory area.[4] DPA-threads are created when readers request attachment to this reflective memory area. In the case when a ReMA is created by a reader, the QoS will be replaced by a writer's QoS later. The global definition table will be updated when other information regarding a particular ReMA becomes available.

3.2.2 Mapping and Attachment

Once created, a reader can "attach" itself to a ReMA by allocating a corresponding reflective memory area on the reader's local node and associating these two remote reflective memory areas. The reader's real-time data reflection requirement is specified as a) periodic (with or without a deadline), b) upon every data update, or c) conditional (i.e., when some condition X becomes true). The reader's period or minimum interarrival time must be greater than or equal to the update period of the writer's reflective memory area. The attachment to an ReMA includes the following actions:

1. The reader specifies its data reflection QoS requirement (i.e., type a), b), or c) as described above).
2. The reader also specifies the number of past data copies (i.e., history) H it requires.
3. Upon receiving a reader's request, the following must be done:
    - 3.1. The schedulability on both the reader's and writer's nodes must be examined by LCAC and GCAC (Local and Global Connection Admission Control). LCAC on the reader's node examines whether the data reflection QoS requested by the reader can be scheduled on the reader's local CPU. Similarly, the LCAC on the writer's node must check the schedulability of the DPA-thread with the QoS requested by the reader on the writer's CPU. The reader's QoS must be equal to or less strict than that of the writer's. Meanwhile, GCAC examines the schedulability of the data reflection QoS requirements on the network. The attachment of a reader to a ReMA can be admitted into the system only when both LCAC and GCAC are successful. We discuss the algorithms used for LCAC and GCAC in Section 5.
    - 3.2. Sets up a connection between the reader and the writer according to the reader's QoS.
    - 3.3. Allocates a circular buffer area of size = N * the size of one reflective memory area. This circular buffer is shared (or mapped to) between the application and the network interface (where the network interface supports direct memory access [11] by the interface card) or between the application and an RT-CRM receiving thread (where the network interface does not support direct memory access by the interface card). Note that this set of N buffers is allocated on the reader's machine. (How to determine the minimum value of N will be described in Section 4.2.)
    - 3.4. Creates a data push agent thread, DPA_thread, on the writer's node on behalf of the reader. This thread will either be a periodic thread or a thread waiting on a signal. Once activated (either periodically or upon an update signal), this DPA_thread will lock and read the reflective memory area, unlock, and transmit the data over the established VC.

Similarly, a writer can "map" itself to a ReMA. If the ReMA has been created by a reader, this mapping includes allocating a corresponding reflective memory area on its own node.

Since a reader's real-time data reflection requirement can be specified as a) periodic, b) upon every data update, or c) conditional (i.e., when some condition X becomes true), DPA_threads can also be of three types, respectively. DPA_threads of type a) are asynchronous with respect to the writer's thread, while DPA_threads of type b) and c) are synchronous. If the reader requires data reflection of types b) or c), the corresponding DPA_thread may be signaled whenever the writer thread completes a write operation in the reflective memory area. Since the periodic writer thread is an application thread, it should only do the write operation in a critical section and then release the lock. Whether the writer thread should evaluate conditions to activate any DPA_threads (for type c) data reflection) depends on the specific application. For example, if the writer is associated with an operator's command task, then the writer thread should wake up the DPA_thread to transmit the operator's commands. On the other hand, if the writer is a periodic sensor, there may be many DPA_threads reading/waiting on the associated reflective memory area. Then, we do not want to force the writer's thread to take the responsibility of evaluating conditions and signaling all the waiting DPA_threads.

3.3 Support for Application Programming

Our design of the RT-CRM with an underlying writer-push model and the DPA-threads allows us to decouple how

4. This network-wide global table is only a logical design. To address bottleneck and reliability issues, the actual implementation can be distributed—one option is for each node to keep a local copy of the table and a separate control channel is set up such that table updates can be broadcast to all nodes. Since table updates do not occur frequently, this will not result in wasted usage of network bandwidth.

TABLE 1
S = Synch., A = Async., B = Blocking, N = Nonblocking, AtA = Application-to-Application, MtM = Memory-to-Memory

Combination	Data Transmission	Delay Bound Required	Application Example
SB	Sporadic	AtA	Command issuing
AB	Periodic	AtA	Trend graph
SN	Sporadic	MtM	Plant data
AN	Periodic or Sporadic	MtM	Video or file transfer

data is updated on the writer's node from how the data is reflected to the reader. Given a reflective memory area, since a DPA-thread is a separate thread of control from the writer's application thread, the DPA-thread can either push the data to the reader's node synchronously or asynchronously with respect to the write operations conducted by the writer's thread. In particular, RT-CRM supports the following types of data push and read operation modes:

- Data Push Operations:
  - *Synchronous Data Push*: Pushes are triggered by application writes.

    When the writer's application thread does a write in the reflective memory area, the DPA-thread sends/pushes the contents of the reflective memory area to the reader/receiver immediately or conditionally. This can be implemented with a signal to the DPA-thread from the writer's thread.
  - *Asynchronous Data Push*: Pushes are performed periodically.

    The DPA-thread sends the contents of the reflective memory area to the reader periodically, i.e., with independent timing from that of the writer's application.
- Read operations:
  - *Blocking Read*: Application reads block while awaiting the arrival of a data update from the writer's node. When the new data is received, the reader application thread is signalled.
  - *Nonblocking Read*: Application reads return the current contents of the reflective memory area. That is, the reader's application thread will not be notified upon the arrival of data update messages.

With this set of data push and read operation modes, we can support at least four combinations for application programming, as listed in Table 1. In the table, the Combination column lists the possible data-push and read operation mode. With respect to each type of Combination, Data Transmission shows the corresponding traffic that will be generated into the network, Delay Bounds defines what level end-to-end QoS guarantee RT-CRM must provide, and Application Example gives the potential usage of the Combination. For example, to implement remote operator command issuing, one can use the combination of SB, i.e., as soon as the operator enters a control command, the corresponding DPA-thread will be signaled to push the command data to the appropriate plant controller, while blocking read is used on the plant controller computer to receive the remote command. This combination provides Application-to-Application delay guarantee. On the other hand, one can imagine situations where only Memory-to-Memory delay guarantee is required. In these cases, the application designer can choose the nonblocking read mode.

3.4 Application Programming Interface

We provide 16 basic interface functions for applications to access RT-CRM services. Table 2 lists the API of RT-CRM. Most of the API are intuitive. Below, we discuss a few that contain special features.

`CRM_Create` creates a reflective memory area entry in the global reflective memory area definition table. A globally unique id for this reflective memory area is returned in `m_id`. The value of `m_mode` can be either **shared** or **exclusive**. If `m_mode` is set to **shared**, more than one local thread can map this reflective memory area into its address space and thus become the writer of the reflective memory area. To allow different threads to map to the same memory area will allow the application threads to be upgraded/modified/replaced at any time without having to reestablish network connections or to recreate DPA-threads. In this way, RT-CRM can become the plug-and-play interface points. Also, allowing more than one local asynchronous threads to access/write into the same memory area provides flexibility to writer applications. If two application threads want to reflect their values to the same reader, they can do so. On the other hand, there might be applications that would like to restrict the number of writers of a reflective memory area to be only one for security or safety reason. Then, the value of `m_mode` should be set to **exclusive**.

If the reflective memory area has not been created yet (this would be the case if the ReMA has been created by a reader), `CRM_Map` creates a reflective memory area of `m_H` buffers, with each buffer equal to the size specified in the global reflective memory area definition table, then maps the reflective memory area pointed to by `*m_addr` to the calling thread. If the reflective memory area already exists, then the calling thread must reside on the local node where the reflective memory area is allocated and this memory area must have been created with the the value of `m_mode` equal to **shared**. With this library function, we allow a reflective memory area to have more than one local writer thread.

As we described at the beginning of the paper, usually an operator would like to be able to monitor a subset of the controllers and devices in a system and, at times,

TABLE 2
RT-CRM Application Programming Interface

//* Creates a reflective memory area by making an entry in the global reflective memory area definition table. *//
`CRM_Create(int m_size; int m_w_period; void *m_addr; int m_mode; int m_id)`
//* Removes the reflective memory area identified by `m_id`. It also terminates all of the DPA-threads and the network channel connections to the readers associated with this memory area. *//
`CRM_Destroy(int m_id; void *m_addr)`
//* Allocates a reflective memory area of `m_H` buffers. Maps the reflective memory area pointed to by `*m_addr` to the calling thread. This memory area must have been created with the the value of `m_mode` equal to **shared**. *//
`CRM_Map(int m_id; void *m_addr; int m_H)`
//* Tears down the mapping between the calling thread and the reflective memory area. *//
`CRM_Unmap(int m_id)`
//* Allocates a reflective memory area of`m_H` number of buffers if `*m_addr` is null. Attaches a reader's thread to the reflective memory area and establish network connections with the writer's ReMA. *//
`CRM_Attach(int m_id; int m_H; int m_r_period; int m_deadline; void *m_addr; int DR-FLAG)`
//* Detaches a reader thread from the reflective memory area by removing the associated DPA-thread and its connection. *//
`CRM_Detach(int m_id)`
//* Activates the associated DPA-thread on the writer's node for the calling reader thread. *//
`CRM_Start(int m_id)`
//* Fills the reader's buffers with existing data from the writer's buffers. *//
`CRM_StartInitH(int m_id; void *m_addr)`
//* Halts the reflection of the memory area by suspending the associated DPA-thread. *//
`CRM_Stop(int m_id)`
//* Read a single memory buffer. By definition, it will be the most recent available data. *//
`CRM_Read(int m_id; void *m_addr)`
//* Read `h` buffers counting back from the most recently updated buffer. *//
`CRM_ReadH(int m_id; void *m_addr; int h)`
//* Read all available data in the buffers. `howmany` returns the number of data buffers read. *//
`CRM_ReadAll(int m_id; void *m_addr; int howmany)`
//* Writes the data pointed to by `*m_data` into the memory area pointed to by `*m_addr`. *//
`CRM_Write(int m_id; void *m_addr; void *m_data)`
//* Locks the memory area for exclusive use. Priority Inheritance must be enforced here. *//
`CRM_Lock(int m_id)`
//* Releases the lock of the memory area after exclusive use. *//
`CRM_UnLock(int m_id)`
//* Resets all the contents of the reflective memory area. *//
`CRM_Reset(int m_id)`

operators switch the membership of this subset. In particular, to optimize the usage of memory, we would like to use the same memory buffer on the reader's node to potentially receive data reflected from different writers. The API functions `CRM_Attach`, `CRM_Start`, `CRM_Stop`, and `CRM_StartInitH` support this flexibility. With `CRM_Attach`, a reader can use the same local memory area to attach to different remote reflective memory areas. When the reader needs to switch from the data reflected from one writer to that of another, `CRM_Stop` will halt the reflection of a memory area by suspending the associated DPA-thread on the current writer's node and `CRM_Start` will activate the associated DPA-thread on the other writer's node for the calling reader thread. Then, `CRM_StartInitH` will fill the reader's buffers with existing data from the new writer's reflective memory area.

4 Implementation Issues

In this section, we address a few important implementation issues. These include concurrency control for read and write operations to the same reflective memory area, buffer management schemes, and QoS guarantees.

4.1 Concurrency Control and Synchronization

For predictability, we strictly impose writer-push for updates. Reflective memory has always been writer-pushed. This also is useful for video transmission. All locks/semaphores are local. All *read* operations are local in nature, even though the writer/owner of the reflective memory area is remote. That is, we do not need to deal with remote reads and page faults. Each reader has an agent thread on the writer's machine representing the reader, called the data push agent thread (DPA-thread). This thread performs the read locally on the writer's machine and then sends the read value via the network into the reader's address space on the reader's machine.

On a writer's node, two alternative methods for concurrency control are used. If the data item to be reflected is of size less than or equal to one word (32 bits) and the writer node is a single CPU machine, then we can safely allow the write and reads to occur concurrently. This is actually quite often the case in real-time monitoring and control applications, where the sensor data is generally some integer number. On the other hand, if the application is dealing with more complicated data, we use lock-based concurrency control between the writer's thread and all the readers' DPA-threads for potential read-write conflicts. One single semaphore is used for one-writer-multiple-reader access of a particular reflective memory area on the writer's machine. The semaphore state should be set to priority inheritance to avoid unbounded wait of the writer when one or more readers are waiting simultaneously for the semaphore. This way, we can ensure that the writer will not block more than one reader's critical section since the writer has a higher priority than all the other reader threads. For scalability, reads with the same QoS should be grouped together as one read operation.

On the reader's node, no locking is needed. Concurrency control is done via sufficient buffer replication as described below.

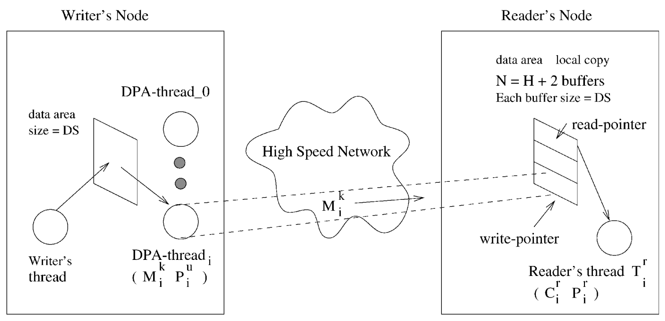

Fig. 4. Terminology illustration for buffer management.

4.2 Buffer Management on Reader Nodes

In this section, we describe the details of how the buffer space on the reader's node is managed in RT-CRM for correct and efficient data reflection.

4.2.1 Overview

Upon a reader's request to attach to a specific reflective memory area D, we allocate a circular buffer area of size = $N * DS$ that is shared (or mapped) between the reader application and the network interface (or a message receiving thread), where DS is the size of the reflective memory area D. (See Fig. 4.) This set of N buffers is allocated on the reader's machine. Among the set of QoS parameters provided by the reader for its reflective memory area attachment, the amount of past data history required by the reader is specified by H. The value N is calculated from H. If the reader needs a maximum H of past data, N will be equal to $H + 2$. For example, if the reader only needs a single copy of the reflective memory area (i.e., the most recent available data), N will be equal to 3. This buffer allocation scheme simplifies the design—*we do not need locking on the reader's node*. A *write-pointer* is used that points to the next buffer area in the circular buffer into which that the next new incoming data will be written. Then, the reader application can always read the buffer area until it reaches the buffer just before the *write-pointer*. This design also supports history or other types of higher level applications (e.g., video transmission) that need to read more than one buffer at a time.

The design of the buffer management for RT-CRM includes a proof of the minimum value for N and a concrete design that uses only the minimum number N of buffers, including the specification of a set of primitive operations for reading and writing the buffers, and the implementation details of a set of basic API. These are described in the following sections.

4.2.2 Minimum Value of N

Locking restricts concurrency and also is an expensive operation, especially if it is required for every read and update operation. Thus, we would like to avoid using locks as much as possible in our design. In this section, we prove that $N = H + 2$ is the minimum number of buffers that is necessary and sufficient to avoid locking each buffer for concurrent reads and/or updates on the reader's machine under the assumptions discussed below. Since *MidART* is a distributed real-time system, to prove the minimum value for N, we must reason about the worst case scenario between the reads and updates, taking into consideration the minimum interarrival time of the reads and the updates, as well as the worst case network jitter that the update messages will incur.

Terminology, Assumptions, and the Worst Case Scenario. DPA_thread_i is a thread on the writer's machine to reflect data to the reader according to the reader's QoS. Thus, DPA_thread_i will transmit a data update message M_i^k to the reader's node either periodically or with a minimum interarrival time. Let P_i^u be the period or the minimum interarrival time of the messages from DPA_thread_i for an application reader thread T_i^r. Remember that P_i^u has already been guaranteed for DPA_thread_i when DPA_thread_i was created at the time the reader attached itself to the reflective memory area. Let C_i^r be the worst case computation time of the operations in thread T_i^r that 1) calculate the index to a buffer to be read next and 2) read the buffer. Thus, with respect to the particular circular buffer used by T_i^r on the reader's node, P_i^u is the period of the writes.

We assume that $C_i^r < P_i^u$. This is a very reasonable assumption since reading the contents of a local data buffer should require less time than the time required to 1) transmit the same amount of data over the network and 2) writing the data into the data buffer.

Due to network queuing and packet scheduling jitter, any data update message M_i^k from DPA_thread_i can experience a maximum network delay of $D_{M_i^k}^{max}$ and a minimum network delay of $D_{M_i^k}^{min}$. If M_i^k incurs $D_{M_i^k}^{max}$ and M_i^{k+1} only incurs $D_{M_i^k}^{min}$, then the two updates from M_i^k and M_i^{k+1} will be *back-to-back*, i.e., M_i^k will update the data buffer at the end of the current P_i^u while M_i^{k+1} will update the next data buffer at the beginning of the next P_i^u. This is the worst case scenario we must guard against when a reader is reading a buffer to avoid race conditions.

We prove the following theorem for the minimum number of buffers needed to allow concurrent reads and writes into the circular buffer without locking.

Theorem 1. $N = H + 2$ *buffers are necessary and sufficient to ensure that concurrent reads and writes are not issued to the same buffer.*

Proof. We will prove for the case of $H = 1$ since it implies the general case for all $H > 1$. That is, we will prove for $N = 3$.

Necessary: Since we need at least two buffers to accommodate the worst case when updates from two messages M_i^k and M_i^{k+1} arrive *back-to-back* from the network in any two consecutive P_i^u periods, we must have a third buffer for reading concurrently. Thus, the *necessary* part is obvious.

Sufficient: Let the buffers be indexed by $I = \{1, 2, 3\}$ and a *write-pointer* always points to the buffer that is either currently being updated or is the next buffer to be updated if no update operation is in progress. Assume that reads and writes always proceed from buffer I to buffer $(I + 1) \bmod 3$. In this protocol, the read starts at (*write-pointer* + 2) $\bmod 3$.

Suppose that the current *write-pointer* is pointing to buffer 1 and a read starts in buffer 3. Since we know that $C_i^r < P_i^u$, then even in the worst case when a *back-to-back* update occurs—as soon as the read starts, the write into buffer 1 completes and the *write-pointer* is incremented to buffer 2—we are still guaranteed that the read in buffer 3 will finish before the write to buffer 2 can complete. Thus, $N = 3$ is sufficient. □

4.2.3 A Design with $N = H + 2$ Buffers

In this section, we first give a concrete design of a circular buffer with a set of associated primitive operations. Then, we will show how to use the design to implement the associated API functions in RT-CRM.

We define a circular buffer area as a memory area allocated on the reader's node and consisting of (see Fig. 5):

- N reflective memory area buffers, each reflective memory area buffer is of size DS, where $N \geq 3$,
- an index I for each buffer, where $I = \{1, 2 \ldots, N\}$,
- a *write-pointer* that always points to the buffer which is either currently being written into (i.e., being refreshed) or is the buffer to be written into next if there are no write operations in progress, and
- a *read-pointer* that points to the buffer that is currently being read.

Below is the set of protocols for primitive read and write operations that must be followed.

- All read and write operations are always performed in the direction of increasing values of $I \bmod N$.
- **Start read**
  - If I is the index of the buffer that the *write-pointer* is pointing to, then the start read operation will return the buffer indexed by I', where

$$\begin{aligned} I' &\geq (I+2) \bmod N \quad \text{if } N > 3 \\ I' &= (I+2) \bmod N \quad \text{if } N = 3. \end{aligned}$$

- **Stop read**
  The read operation always stops at the buffer indexed by $I'' = (I - 1) \bmod N$, where I is the buffer pointed to by the *write-pointer*.
  Note that if only the most recent data is to be read, then **Start read** will be the same as **Stop read**. In the case of $N = 3$, one should notice that $(I + 2) \bmod N$ is the same as $(I - 1) \bmod N$. Thus, for $N = 3$, we always read the buffer that is two away from the *write-pointer*. However, when $N > 3$, we must use the calculation in **Stop read** for reading only the most recent data buffer.
- **Write**
  - Write the new data into the buffer I pointed to by the *write-pointer* and move the *write-pointer* forward such that $I = (I + 1) \bmod N$.

Algorithms *M_Read*, *M_Read_History*, and *M_Read_All* implement the API functions `CRM_Read()`,`CRM_ReadH()`, and `CRM_ReadAll()`, respectively. The algorithms are presented in pseudocode shown in Figs. 5, 6, and 7. In Figs. 6 and 7, t_0 is the time when the read operations start and t_e is when the read operations complete.

```
Algorithm M_Read
begin
Read write-pointer I;
Read buffer ((I-1) mod N);
end
```

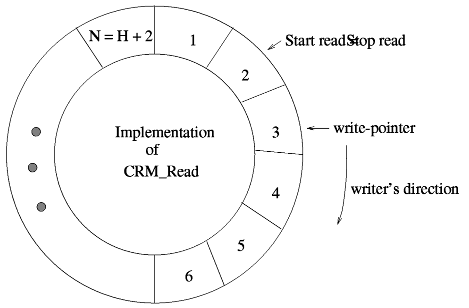

Fig. 5. Reading the most recent reflective memory area.

5 Discussion

Although we do not directly address the problem of network interface design and the problem of QoS guarantee algorithms for the host system and the network in this paper, these are issues that closely influence how RT-CRM achieves its goals.

5.1 Network Interface Support

The RT-CRM architecture on the reader side can be implemented in two ways, depending on the type of network interface hardware and software available.

1. With direct memory deposit capability from the network interface, such as those discussed in [11],

```
Algorithm M_Read_History
begin
 Read write-pointer I;
 I' = ((I + 2) mod N) + (H-h);
 for i = 1 to h do
 Read buffer I';
 I' = I' + 1;
end
```

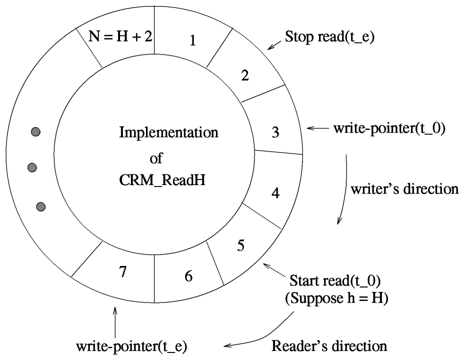

Fig. 6. Reading a history of size h.

```
Algorithm M_Read_All
begin
  Read write-pointer I;
  I' = (I + 2) mod N;
  while I' not equal to ((I - 1) mod N) do
  Read buffer I';
  I' = I' + 1;
end
```

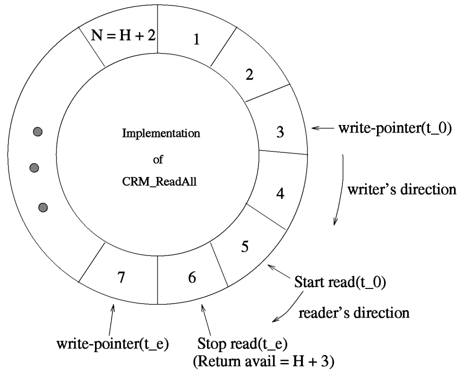

Fig. 7. Reading all available history up to now.

we do not need a receiving thread in the middleware on the reader's node. Upon receiving a message with the newly updated data from a DPA-thread, we can identify the memory area/buffer address into which the data update message should be written and do the correct calculation for the circular buffer indexes, as described in Section 4.2. This will no doubt provide a much more efficient and low latency data reflection path.

2. Without any direct memory deposit facility from the network interface, we will need to create a receiving daemon or driver thread on the reader's node. This daemon thread will be mapped into the same data area circular buffer memory as our application reader's thread. This is our current implementation since we do not yet have any network interface with direct memory deposit capability available.

5.2 End-to-End QoS Support

Although real-time task scheduling in the host system, as well as network message transmission scheduling, is orthogonal to the issues that RT-CRM addresses, RT-CRM relies on these underlying end-to-end scheduling mechanisms to guarantee the timeliness of the data push operations. There is a large body of research results on the subject of real-time task scheduling and real-time message communication. In particular, for the first target network for RT-CRM, ATM, we used ATM traffic class CBR, which provides a constant cell rate service and bounded cell delay variation. Real-time communication can be supported by this traffic class with appropriate network switch scheduling [1], [17]. For scheduling the DPA-threads, writers as well as readers in the host systems, we used rate-monotonic scheduling algorithms [5], [12] with operating system support on QNX. In our current implementation on Windows NT 4.0 over Fast Ethernet, the end-to-end support is achieved via 1) explicit rate control of the amount of communication at the sending nodes and 2) user-level dual priority scheduling of real-time threads in Windows NT [15].

Moreover, in scheduling a writer thread and the DPA-threads associated with the same writer's reflective memory area, we use a Writer-QoS based correctness model—the writer has higher priority over readers (i.e., the DPA-threads). This is because the writer is usually constrained by either the physical plant control components (e.g., sensor sensing rate) or the operator's command issuing timing constraints. In either case, it does not make sense to give the writer a lower priority than the readers.

6 Performance Evaluation

6.1 Performance over ATM with Real-Time Operating System Support

We have implemented the first version of RT-CRM on an ATM-based LAN environment. The host systems are Digital's VENTURIS FX (Pentium 133Mhz, PCI bus) PCs running QNX real-time operating system version 4.23. Since our version of QNX does not support POSIX threads, we implemented all the DPA-threads as processes. The network interface cards on the PCs are FORE Systems PCA-200ePC for PCI bus. We used one ATM switch, FORE Systems ASX-200BX, to connect the host systems. Since current ATM software does not support CBR and rt-VBR traffic classes in switched virtual channels, our implementation used PVCs. We would like to eventually implement RT-CRM using native ATM, but again, currently for the first version, we must live with available commercial ATM software which only supports IP interface.

We focused our performance tests on two aspects of RT-CRM. One is how much overhead RT-CRM really incurs compared with raw UDP/IP. The other is the delay in switching from one writer's ReMA to another writer's ReMA for a reader. Table 3 lists the tasks and the parameters we used in all of our experiments reported here. All the writer tasks and the DPA tasks reside on one host, while all the reader tasks reside on a remote host. The priorities of tasks are such that a higher number indicates a lower priority. Since it is very difficult to measure the overhead for one-way communication in a LAN environment without sychronized clocks, our measurements are all round-trip times. To do this, we must use synchronous data push operation mode and blocking read, as described in Section 3.3. In particular, our overhead measurements were all done with respect to writer #5, DPA #5, and reader #5 in Table 3. In the performance results shown below, for each data message size, we did 100 runs on an unloaded system and network and extracted the minimum, the maximum, and the average latencies.

Table 4 shows the performance of round-trip latency *RTT*. To compare the round-trip latency of RT-CRM with that of raw UDP/IP, each measurement includes the time executing the following steps:

- Writer #5 starts a timer and writes into the ReMA on its own local node.
- Writer #5 signals DPA #5.
- DPA #5 sends data to the reader host.

TABLE 3
Task Parameters

Tasks	Period (sec)	Priority	Mode
writer #1	1.00	19	
writer #2	0.50	21	
writer #3	0.20	23	
writer #4	0.10	25	
writer #5	0.05	27	
DPA #1	1.00	20	ADP
DPA #2	0.50	22	ADP
DPA #3	0.20	24	ADP
DPA #4	0.10	26	ADP
DPA #5		28	SDP
reader #1	1.00	19	NBR
reader #2	0.50	19	NBR
reader #3	0.20	19	NBR
reader #4	0.10	19	NBR
reader #5		19	BR
receiver		29	

ADP = Async data push, SDP = Sync data push, NBR = Non-blk read, BR = Blocking read.

- A receiver task on the reader host receives the data and deposits into the ReMA.
- Reader #5 reads the data and sends an acknowledgment back to the writer's host to stop the timer.

The worst-case and average round trip time *RTT* in Table 4 is almost proportional to messsage size. And, more importantly, most of the *RTT* is the overhead of IP/UDP itself. RT-CRM itself incurs very little extra overhead.

Table 5 shows the total latency in switching from one writer's ReMA to another writer's ReMA for a reader. This switching incurs two round-trip overhead cost. It requires a reader to send stop control signal (using the `CRM_Stop` call) to the current writer and, upon receiving an acknowledgment, the reader sends a start signal (i.e., `CRM_Start` call) to a different writer. Only after receiving the newly reflected data from the second writer do we stop the timer for measurement. This experiment tells us whether RT-CRM can support interactive RT-CRM memory channel switch for plant operators. In this experiment, the reader makes a request to switch from writer #4 to writer #5 every 1.01 sec. We used such a period in order to avoid phasing problems between the switching requests and write operations in the writer node. Strictly speaking, the performance numbers shown in Table 5 really includes the waiting time for the next period of writer #5 and, therefore, we should expect a difference between the min and max of about 50 msec (i.e., the period of writer #5). Thus, the min values should be very close to the *pure* switching time of RT-CRM. Remember that the latency requirement for this switching operation in our application domain is the actual interactivity requirement of the human operator with the machines. The min values are definitely sufficient for human operator interactivity requirement.

6.2 Performance over Fast Ethernet with Windows NT

The objective of our performance tests is to characterize and validate our current implementation. In particular, we are interested in the following three aspects about our implementation: 1) measure the application-to-application latency introduced between the writer and the reader of a ReMA, 2) determine the overhead that RT-CRM incurs compared with raw UDP/IP, and 3) measure the overhead costs of certain non-real-time API calls involved in the creation/destroy of reflective memory areas.

The performance experiments discussed below were conducted using two single CPU Pentium Pro 160MHz PCs with 32MB of RAM running Windows NT 4.0. We used an Eagle FastEthernet switch from Microdyne to connect the two machines.

6.2.1 Latency

To determine the latency introduced by RT-CRM, we again measured the application-to-application round-trip time (RTT) of a write event. For all of the experiments described in this section, each data point is the result of 1,000 runs on an unloaded system and network.

In our first experiment, we create a writer thread at one node and a reader thread at the other node. The reflective memory area is attached under a synchronous data push operation mode and blocking read mode. The period for the writer is 50 milliseconds. Figs. 8 and 9 show the average and

TABLE 4
Round Trip Latency

msg size (byte)	UDP(avg)	UDP(max)	RT-CRM(avg)	RT-CRM(max)	ratio(avg)	ratio(max)
1	2.710293	3.300402	2.977183	3.337278	1.10	1.01
512	3.172350	3.742914	3.545074	4.047141	1.12	1.08
1024	3.571846	4.572624	4.097753	5.319363	1.15	1.16
1536	3.895765	4.526529	4.516572	5.116545	1.16	1.13
2048	4.268332	5.678904	5.723155	7.153944	1.34	1.26
2560	4.660573	5.807970	5.806402	6.785184	1.25	1.17
3072	4.878141	6.075321	6.586975	8.121939	1.35	1.34
3584	5.190481	6.324234	6.737245	8.002092	1.30	1.27
4096	5674294	7.052535	7.611298	10.666383	1.34	1.51

ratio - RT-CRM/UDP. Time is in msec.

TABLE 5
ReMA Switching Latency

msg size (byte)	max	min	avg
1	59.103009	9.136029	34.579086
512	58.420803	10.168557	34.222680
1024	60.126318	10.242309	35.609863
1536	62.495601	10.306842	36.405831
2048	60.089442	11.035143	35.974197
2560	61.675110	11.579064	36.941271
3072	62.255907	12.252051	37.623661
3584	61.739643	12.288927	37.094951
4096	67.298700	12.740658	38.838356

Time is in msec.

maximum RTT, respectively, for different message sizes and Windows NT priority classes assigned to threads involved (DPA, receiver, writer, and reader). The priority classes are: Real-Time, High, and Normal. For each performance curve, all the threads involved in the measurements are assigned to the same priority class. One important result of this experiment is that, under all the class priorities, the average RTT is acceptable for a wide range of applications. The worst case (i.e., maximum) only occured very rarely. We are currently investigating the cause of such worst case occurrences. Moreover, the worst-case RTT using Real-Time priorities remains linearly proportional with the message size, which is not the case for the other two priority classes.

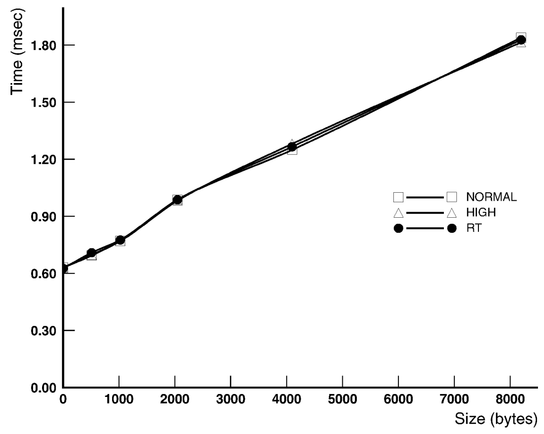

Fig. 8. Average RTT with one writer.

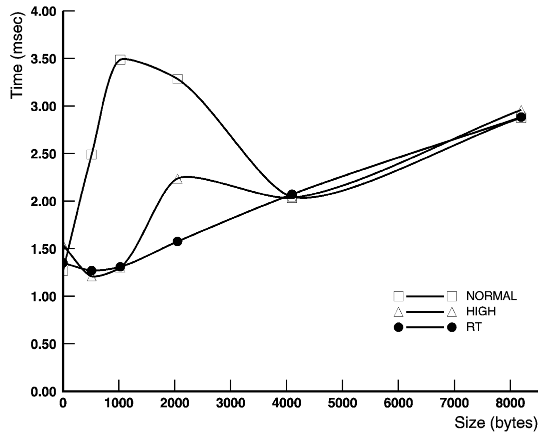

Fig. 9. Maximum RTT with one reader-writer.

TABLE 6
Round Trip Latency

msg size (byte)	UDP(avg)	RT-CRM (avg)
1	0.459240	0.626410
512	0.526845	0.709782
1024	0.582634	0.776303
2048	0.763597	0.988170
4096	0.978962	1.266156
8192	1.460686	1.828897

Time in msec.

The overhead that RT-CRM incurs compared with raw UDP/IP for this experiment is shown in Table 6. The major source of overhead cost comes from the additional memory-to-memory copies done in RT-CRM.

We have done additional experiments measuring the stability of the RTT with interfering load in the system. Instead of running only one application writer-reader pair, we vary the number of write-reader pairs from 1 to 50 and measure the stability of the RTT for the writer-reader pair with Windows NT's highest real-time priority and a period of 50 msec. All other readers and writers have lower priorities—50 percent of them have Windows NT's normal real-time priority with a 100 msec period and the other 50 percent have below normal real-time priority with 200 msec period. Our results in Fig. 10 show that the end-to-end delay is quite stable.

6.2.2 Overhead Costs of API Calls

Overhead costs of the API calls are important in order to obtain a characterization of the implementation on Windows NT. At the same time, they provide us with feedback, which can be used to fine tune the implementation or to review some of the design decisions made. The cost of each of the calls evaluated is shown in Table 7. Each

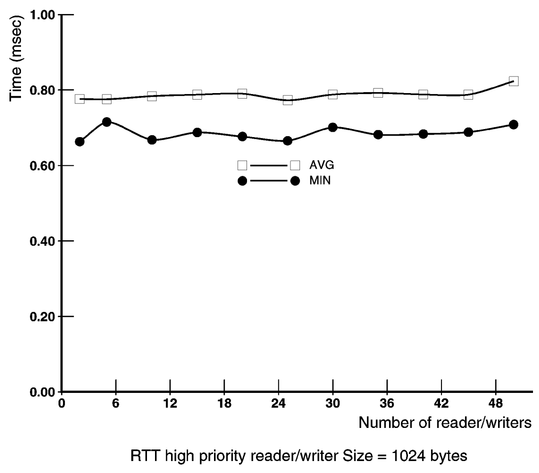

Fig. 10. Round trip latency of the highest Priority real-time writer-reader.

TABLE 7
Overhead Cost of API Calls in Milliseconds

API Call	Average	Maximum
Create	7.144702	7.854627
Destroy	3.134065	3.27359

data point is the result of 100 runs in an unloaded system and network.

A Create call incurs more overhead because it must go through the following steps:

1. Contacts global server to obtain id.
2. Creates memory area (allocates buffers and locks them into memory).
3. Creates mutex for read/write access.
4. Creates an event to synchronize with DPA thread.

7 Concluding Remarks

We have described in detail the design, API, implementation, and preliminary performance results of RT-CRM. We demonstrated how distributed real-time applications can utilize RT-CRM to facilitate its remote data reflection. Our performance tests show that RT-CRM incurs very little overhead and is a feasible solution for many real-time application environments.

The proposed RT-CRM is similar in many ways to the Publisher/Subscriber model [13] found in many of today's distributed programming services. The key difference is our emphasis on data distribution as memory-to-memory data transfer, rather than as message passing.

RT-CRM has been applied to two industrial applications. One is a LAN-based power plant control system. The other is a water treatment plant. RT-CRM can be obtained for research purpose as part of the real-time network middleware package MidART [3]. To fully explore the potential of RT-CRM as a standard real-time communication service model, further research is underway to construct RT-CRM as a new CORBA service [4].

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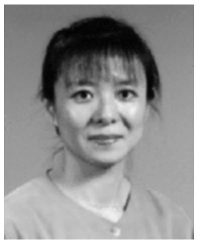

Chia Shen received her MS and PhD degrees in computer science from the University of Massachusetts, Amherst, in 1986 and 1992, respectively. In her PhD thesis research, she worked in the areas of real-time multiprocessor scheduling theory, resource and task allocation, and multiprocessor operating system support for real-time systems. She is a senior research scientist at MERL, Mitsubishi Electric Research Labs, Cambridge Research Lab in Cambridge, Massachusetts, which she joined in 1992. From 1993-1996, she served as the primary representative in the ATM Forum for Mitsubishi Electric Corp. Dr. Shen's research interest has been in distributed real-time and multimedia systems. She is particularly interested in the nontraditional use of standard high speed networks for future distributed industrial control applications and distributed multimedia environments. Her latest research project, MidART, is a distributed real-time application development software package providing easy-to-use programming interface for real-time data acquisition and communication. MidART supports real-time applications where humans need to interact, control, and monitor instruments and devices in a network environment through computer interfaces. She is a member of the IEEE.

Ichiro Mizunuma received the BS and the MS degrees in information science from Kyoto University, Kyoto, Japan, in 1990 and 1992, respectively. He joined Mitsubishi Electric Corp., Japan, in 1992 and has worked in the Industrial Electronics & Systems Laboratory at Mitsubishi Electric Corp. as a research engineer. In the laboratory, he has engaged in the development of real-time systems, fault-tolerant systems, and distributed systems, mainly for plant monitoring and control applications. He is currently working on intelligent transportation systems as a visiting scientist in the Intelligent Transportation Research Center (ITRC) at the Massachusetts Institute of Technology, Cambridge, since January 2000. Dr. Mizunama is a member of the Institute of Electronics, Information, and Communications Engineers (IEICE), the Information Processing Society of Japan (IPSJ), and the IEEE Computer Society.